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1 January 1964   through   31 March 1964

EVALUATION OF RMSP

TUNGSTEN SHEET

EVALUATION OF RMSP

TUNGSTEN SHEET

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FOREWORD

This is the Third Quarterly Progress Report prepared by the Aerospace Activity of Solar, a Division of International Harvester Company, under contract NOw 63-0786d, Evaluation of RMSP Tungsten Sheet. The contract was issued by the Industrial Readiness Branch, PID-222, Bureau of Naval Weapons, Department of the Navy under Project 3478-62 with Mr. Bernard Bland as the BuWeps Project Engineer and Mr. Irving Machlin as Technical Consultant.

The period covered by this report is 1 January 1964 through 31 March 1964.

The program is designed to develop manufacturing acceptance criteria; evaluate manufacturing techniques for RMSP tungsten sheet, and gain information which can be used for the fabrication of a composite-assembly tungsten sheet component.

The program consists of four phases:

1. Evaluation of general material quality, metallurgical uniformity, and the determination of mechanical properties on different gages of powder metallurgy rolled tungsten sheet

2. Formability determination and joining studies

3. Fabrication cf simple elements

4. Fabrication of a subassembly component

Personnel contributing to the program and the compilation of this report were: Messrs. F. St. Germain, Project Manager; M.R. Licciardello, Technical Consultant; G. Pritchett and D. Jones, Mechanical Testing; L. Mueller and C. Swindall Forming Evaluation.

SUMMARY

The evaluation of the as-received four gages of RMSP tungsten sheets using standard acceptance test techniques was continued. Resistance heated elevated tensile tests, 5T and 6T bend-transition determinations, recrystallization measurements, and chemical analysis for carbon and columbium were performed during the reporting period. The resistance heated mechanical property evaluation for the same equivalent thicknesses showed comparative tensile properties, with lower elongations than those reported by Fansteel for the same temperature range using radiant heating test techniques. The recrystallization measurements indicated that the recrystallization temperatures for the 0.010-, 0.020-, 0.060-, and 0.100-inch sheet, are 2450 F, 2500 F, 2525 F, and 2550 F, respectively. Two sheets of each gage were reanalyzed for carbon and columbium by Wah Chang Corporation. The carbon range was found to be less than 30 ppm to 40 ppm, and the columbium was found to be less than 50 ppm. Bend transition tests conducted on the remaining tungsten sheets showed the highly cold-worked material exhibited the lowest bend-transition temperatures, with ductile-brittle transition temperatures increasing with decreasing amount of cold work. Reverse bending of the material, originally bent to 90 degrees, showed the thin-gage sheet material could be reverse bent flat with less tendency to delaminate than the 0.060-inch and 0.100-inch sheets. The failure of the heavier sheet gage during reverse bending was most predominant at 120 degree to 160 degree bend angles.

Blanking, perforating, and deep drawing investigations were conducted on each of the four tungsten sheet thicknesses. The results of the blanking and perforating studies indicate that these forming methods could be accomplished by control of sheet temperature, close tolerance tooling, and control of forming procedures. Preliminary deep drawing of 0.060-inch tungsten sheet with a drop hammer was not successful. The deep drawing of 0.060-inch and 0.100-inch tungsten sheet was successfully accomplished with steel tooling and a hydraulic press. The results of the deep drawing studies indicate that successful deep recessing of thicker tungsten sheet can be obtained by stage forming at elevated temperatures with conventional tooling and control of the forming process.

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I. INTRODUCTION

Evaluation of the as-received RMSP tungsten sheet using standard methods for acceptance testing, development of shop processes to determine the formability of the four gages of RMSP tungsten sheet, and their applicability for fabrication of a suitable aerospace component represents a condensed statement of the program objectives. Consideration in this program has been given to the basic principles underlying the fabrication and processing of tungsten sheet, since fabricability of tungsten sheet is greatly affected by prior processing history and thermal treatments.

During this reporting period, the activity was in Phases I and II of the program.

The primary concept in conducting this type of program is to establish a series of meaningful and practical tests for determining the quality and forming behavior of tungsten sheet produced under the Refractory Metal Sheet Rolling Program. Standard methods for evaluating the various gages of tungsten sheet were used to the most practical extent. The recommendations and procedures listed in MAB 192-M concerning the testing of refractory metals have been used as a guide in setting up and conducting many of the material acceptance tests for tungsten sheet.

Included in Solar's Quarterly Progress Report No. 2 on the Evaluation of RMSP Tungsten Sheet are the results of:

- Sheet chemical analysis
- Microstructural analysis
- Hardness surveys
- 5T and 6T bend transition temperature determinations
- Elevated-temperature tensile test evaluations
- Hot square shearing evaluations
- Hot rotary shearing evaluations

During this reporting period, Solar continued with the preparation of test specimens for acceptance and formability tests. The remaining elevated temperature tensile tests were completed. The bend transition temperature evaluation on the remaining sheet material was also completed.

The recrystallization temperature determinations and low-temperature tensile tests, as part of the formability studies, were conducted to develop forming paramaters in the blanking and perforating evaluations. Blanking and perforating investigations were conducted on each of the four gages of tungsten material. The results of these two formability studies showed that successful blanking and perforating could be achieved by adequate temperature control of the material and by suitable tooling and forming procedures.

II. TECHNICAL DISCUSSION

2.1 ACCEPTANCE TESTS

2.1.1 Chemical Analysis

The chemical analyses reported in the second quarterly progress report were discussed at the March meeting of the MAB, RMSRP subpanel. The discussion resulted in a decision to recheck the carbon and columbium analyses of selected specimens from each gage of material which had been previously analyzed by an independent test laboratory. Eight specimens (two from each gage of material) were selected at random from the thirty previously analyzed specimens. Chips for the carbon and columbium analyses were prepared by the "rough edge breaking" technique described in Reference 1. The chips were sent to the Wah Chang Corporation, Albany, Oregon for carbon and columbium determinations. The carbon was determined by conductrimetric method, and the columbium by X-ray fluorescence. The results of the chemical analysis is shown in Table I.

TABLE I

CHEMICAL ANALYSIS OF RMSP TUNGSTEN SHEET

Sheet Number	Sheet Thickness (in.)	Element (by weight in ppm)			
		Carbon		Columbium	
		Wah Chang	Solar	Wah Chang	Solar
1	0.010	<30	90	<50	700
16	0.010	<30	96	<50	700
6	0.020	40	91	<50	700
2	0.020	40	87	<50	700
3	0.060	<30	86	<50	700
1	0.060	<30	84	<50	700
65	0.100	<30	91	<50	700
76	0.100	115	84	<50	700

The results of the second analysis for carbon and columbium conducted by Wah Chang indicated a lower carbon content in each sheet checked with the exception of sheet 76 which was rechecked twice with the same analytical results. The reported values ranged from 30 ppm to 40 ppm compared with 84 ppm to 96 ppm in the previous carbon determination. This is approximately a 66 percent decrease.

Although the difference in carbon content is significant, it should be noted that Fansteel (Ref. 2) reported carbon contents of 10 ppm to 20 ppm for the four gages of RMSP tungsten sheet. The analytical differences may be due to laboratory techniques and the sensitivity of the equipment to accurately analyze less than 20 ppm carbon.

No explanation can be given for the wide variation in the carbon determinations reported by two test laboratories. Possibly the carbon pickup might have occurred during process cleaning after the shearing operation or during sample preparation.

The spectrographic analysis performed by Wah Chang revealed a columbium content of less than 50 ppm compared to the previously reported 700 ppm. No definite explanation can be given for the significant difference in values for the same tungsten sheet material. The values reported by Wah Chang for columbium determinations are comparable with those reported by Fansteel (Ref. 3).

2.1.2 Elevated-Temperature Tensile Tests

Elevated-temperature tensile tests, on specimens removed from the longitudinal and transverse direction of the four gages of RMSP tungsten sheet were conducted during this reporting period. The tensile properties of the various tungsten sheet thicknesses were evaluated at 1000 F and 2000 F as part of the acceptance tests for this particular lot of material. A brief description of the test procedure is included in the following paragraphs.

The tensile test specimens described in Reference I were tested on an Instron 60,000-pound capacity universal testing machine at 1000 F and 2000 F. The loads were applied at a strain rate of 0.005 in/in./min through the 0.2 percent yield, then the strain rate was increased to 0.05 in/in./min from yield to failure. The strain rates were controlled by pacing or regulating the crosshead speed under actual loading conditions. Load deflection curves were autographically plotted for each specimen with an Instron recorder. The deflection experienced by each specimen was measured by Tinius-Olsen Model D-4 deflectometer used in conjunction with the Tinius-Olsen Model 51 recorder. The elevated-temperature specimens were heated by self-

resistance in an inert gettered argon atmosphere chamber which had been purged for 30 minutes. This purging time was found to be the minimum that would ensure complete removal of air from the test chamber. The specimens were secured and pinned in the load train by two water-cooled Inconel clevis-type grips and two 0.5-inch Inconel retaining pins. The Inconel grips were fitted into the Instron pull rods. The entire load train was enclosed in a stainless steel test chamber which was fitted with needle valves for argon circulation, a quartz viewing port for temperature observation, and a special port for focusing a radiometer on the specimen.

Power was supplied to the specimens through the pull rods by a 75 kva stepdown transformer controlled by a Research, Inc., Ignitron Temperature and Power Controller. The controller was regulated by the output of a Minneapolis-Honeywell radiometer sighted on the specimen. Test temperature readout was accomplished by sighting a Leeds and Northrup calibrated disappearing filament optical pyrometer on the specimen through the quartz viewing port for the 2000 F tests, and a chromel-alumel thermocouple was attached to the specimen with a Model 8686 Leeds and Northrup potentiometer for the 1000 F tests. The heating rate was 100 degrees F to 125 degrees F per second until the required test temperature of 1000 F or 2000 F was achieved. The specimens were held at test temperature for an additional 60 seconds to permit temperature stabilization.

Emissivity and absorption corrections were applied to the observed optical pyrometer values to obtain the true test temperature.

Tensile test data for each thickness of tungsten sheet are presented in Table II. The tabulation includes sheet number, grain direction, ultimate tensile strength, 0.2 percent yield strength, percent elongation in two inches, and test temperature.

Typical fractures obtained on self-resistance heated specimens of each thickness tested are shown in Figure 1.

The results of the elevated temperature tensile tests on the 0.020-, 0.060-, and 0.100-inch thick tungsten sheet material indicated that the 0.020-inch thick sheets was stronger in both the transverse and longitudinal directions than the 0.060- and 0.100-inch tungsten material; however, the results of the tensile tests of the 0.060- and 0.100-inch thick sheet show that for comparable grain direction and same test temperatures, the tensile properties of the two heavier sheet gages are comparable.
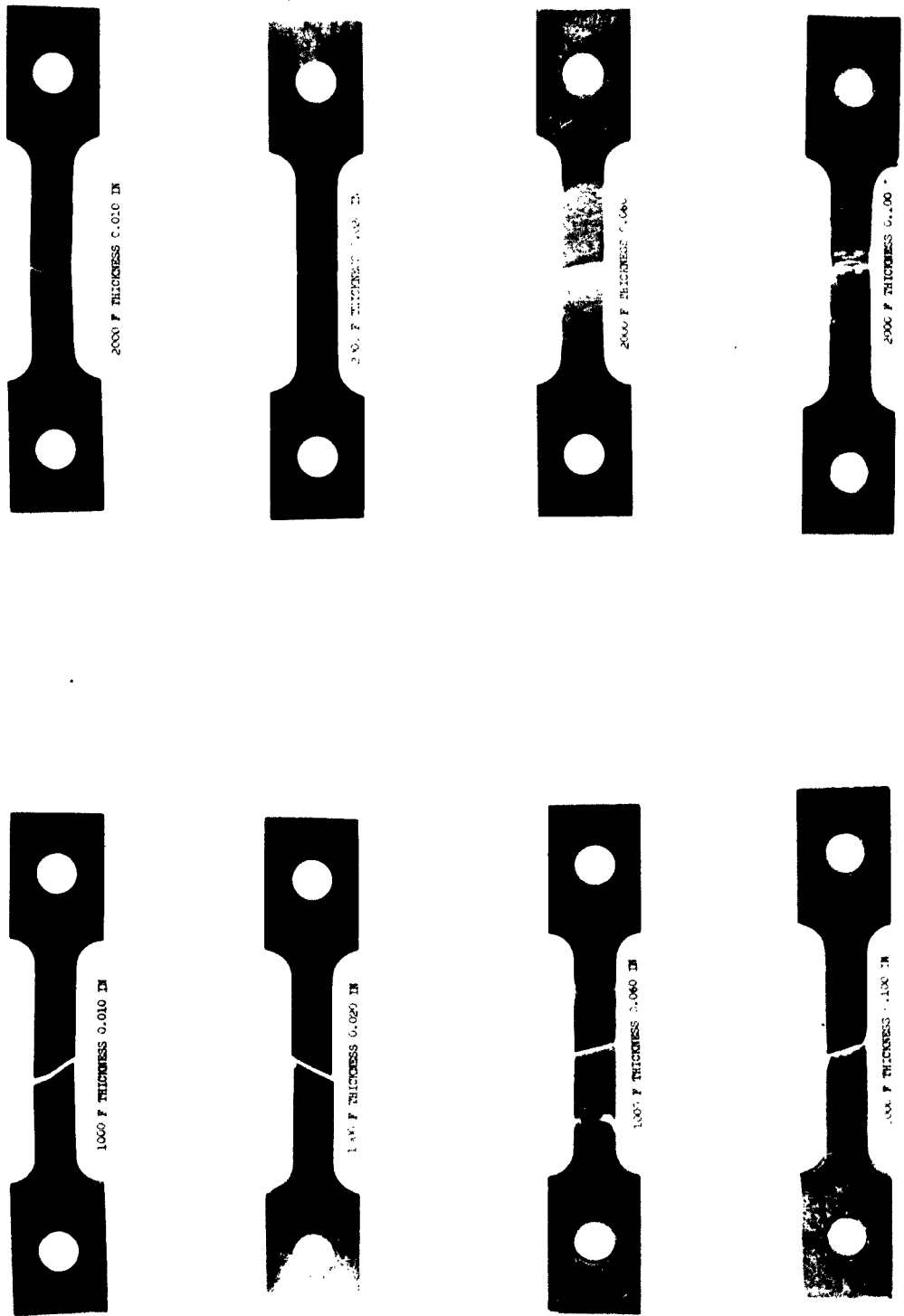
FIGURE 1. TYPICAL FRACTURES OF RESISTANCE HEATED SPECIMENS

TABLE II

TENSILE TEST DATA

Sheet Specimen Number	Test Direction	Test Temperature (F)	Ultimate Tensile Strength (ksi)	0.2 percent Yield Strength (ksi)	Elongation (percent in 2 in.)
		0.020-Inch Tungsten Sheet			
1-2-L-13	Longitudinal	1000	109.2	95.0	1.9
1-2-L-12	Longitudinal	1000	109.1	92.2	1.0
6-2-T-2	Transverse	1000	130.0	95.8	1.5
2-L-12	Longitudinal	2000	69.6	52.8	1.8
1-2-L-8	Longitudinal	2000	70.5	63.8	2.3
2-T-4	Transverse	2000	81.1	63.6	2.2
6-2-T-3	Transverse	2000	81.4	73.7	2.7
		0.060-Inch Tungsten Sheet			
14-L-10	Longitudinal	1000	96.1	83.0	3.0
1-L-10	Longitudinal	1000	94.6	90.3	4.2
3-L-10	Longitudinal	2000	65.6	62.6	4.4
3-L-7	Longitudinal	2000	71.8	65.6	4.2
14-L-9	Longitudinal	2000	67.6	59.2	4.8
2-T-12	Transverse	2000	74.1	68.1	3.9
3-T-1	Transverse	2000	72.3	59.4	4.1
14-T-3	Transverse	2000	66.5	59.2	3.7
		0.100-Inch Tungsten Sheet			
65-L-9	Longitudinal	1000	94.5	87.3	6.1
76-L-7	Longitudinal	1000	87.0	82.6	8.2
76-L-11	Longitudinal	1000	83.4	79.9	8.3
55-T-11	Transverse	1000	97.6	92.0	5.2
64-T-4	Transverse	1000	88.2	86.6	6.0
65-T-5	Transverse	1000	95.0	78.5	5.8
55-T-10	Transverse	1000	93.4	91.4	5.5
76-L-8	Longitudinal	2000	66.9	53.2	7.7
76-L-10	Longitudinal	2000	65.8	50.6	6.3
3-T-3	Transverse	2000	75.6	57.8	6.1
65-T-1	Transverse	2000	76.8	70.2	6.8
76-T-2	Transverse	2000	73.4	62.8	6.4
64-T-3	Transverse	2000	71.4	57.6	5.3

By virtue of the heating method used to conduct the elevated-temperature tensile tests, it was observed that the ductility did not appreciably increase in either of the three gages tested. A direct comparison of the tensile properties given in Table II to those reported by Fansteel (Ref. 2) for the same equivalent thicknesses showed that the tensile properties obtained in the Solar tests were lower but within the range reported by Fansteel. However, the most noticeable difference was in the elongation values.

Fansteel's elongation values were almost twice those obtained by Solar. It was learned that Fansteel had conducted their tensile tests under radiant heating conditions, whereas the Solar tests were conducted by self-resistance heating. At the March meeting the MAB, RMSRP subpanel, the limited ductility on each of the four gages of material tested using self-resistance heating methods was discussed. The panel suggested that additional tensile tests be conducted at the same test temperatures under radiant heating conditions to determine if the low ductility is due to the method of heating the test specimens. It was generally agreed at the meeting that a possible cause of the low ductility could be the severe thermal gradients in the specimen gage length at a discontinuity such as necking or cracking prior to failure. This would result in an increased resistance and localized overheating in the necked down region which would cause erroneous elongation measurements due to a very localized extension in the hottest temperature zone in the gage length.

Although the elevated-temperature mechanical property determinations were carried out under a positive pressure of argon, the low ductility obtained in the resistance heating tensile tests may have been influenced by absorption of interstitial contaminants by the tungsten sheet specimens during testing.

One specimen of each gage of material will be chemically analyzed for carbon, oxygen, and nitrogen to determine if the low ductility results are partially due to absorption of interstitial gases during testing.

Elevated-temperature tensile tests on selected specimens of the four sheet gages, using radiant heating methods, will be accomplished by an outside test laboratory.

The tensile evaluation of 1000 F and 2000 F is just getting started and the data developed in this series of tests will be reported in the next progress report.

If the radiant heating test method indicates a more uniform and higher elongations for tungsten sheet than the resistance heating method, future tensile test evaluations of tungsten sheet during the formability study will be done by radiant heating.

2.1.3 Recrystallization Determination

Four sheets, representing each gage of material, was selected at random for the determination of the recrystallization temperature for that specific material thickness. It was assumed that if each gage lot of material was processed in a like manner, then any sheet chosen would be representative of that material lot. The following sheets were selected:

Gage (in.)	Sheet Number
0.010	5
0.020	6
0.060	14
0.100	65

Since the temperature at which tungsten undergoes recrystallization is determined by prior processing and thermal history, a series of test temperatures were selected which would adequately establish the recrystallization parameters. To adequately determine the onset of recrystallization, 50 percent recrystallization, and complete recrystallization, 3/4 inch by 3/4 inch specimens were used for testing. The test specimens were encapsulated in 0.002-inch tantalum foil and suspended in an enclosed, water-cooled, copper jacket. The specimens were inductively heated in a 3-inch diameter Pyrex tube. Gettered argon gas was flowed over the test specimens to prevent contamination at elevated temperatures. The specimens were heated to test temperatures of 2000 F to 3000 F in 100 degree F increments. The temperature was monitored by a calibrated micro optical pyrometer sighted on the specimen through a sight port in the water-cooled copper jacket. Emissivity and absorption corrections were applied to the observed optical pyrometer values to obtain the true test temperature. The test specimens were held at test temperature for a minimum of thirty minutes and the specimens were cooled in argon to room temperature. The samples were then prepared for metallographic examination. The induction heating equipment with the copper sleeve in place during one of the test runs is shown in Figure 2. The Rockwell surface hardness, mid-thickness DPH, and metallographic estimates of the percentage of recrystallized structure was determined to establish the recrystallization behavior of the four tungsten sheet gages. The metallographic estimates were determined by more than one observer and the results of these independent observations were averaged to obtain the values given in Tables III through VI.
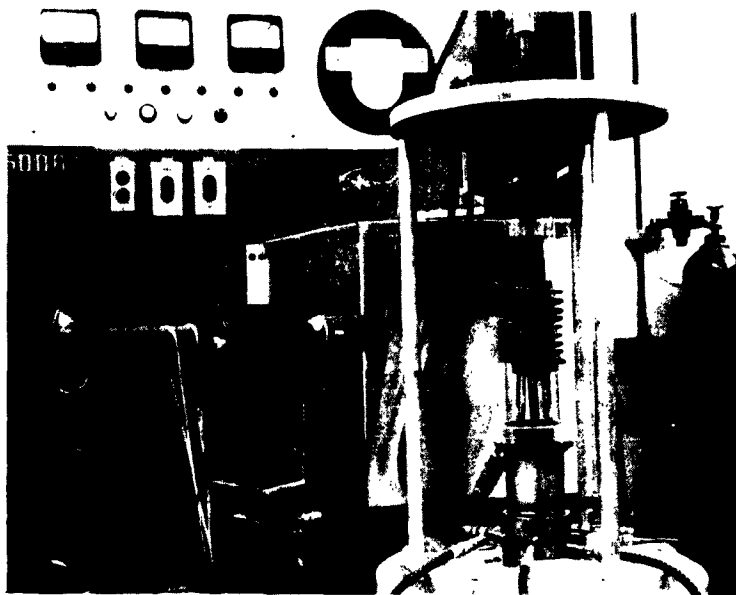
FIGURE 2. INDUCTION HEATING EQUIPMENT FOR RECRYSTALLIZATION STUDIES

The results of the hardness measurements and percent recrystallization for each material gage were plotted as a function of temperature. The data plot (Fig. 3) shows the function of increasing temperature with increasing percentage of recrystallization for the same time and temperature conditions.

TABLE III

HARDNESS AND PERCENT OF RECRYSTALLIZATION
OF 0.010-INCH THICK TUNGSTEN SHEET

Specimen Number	Time at Temperature (min)	Temperature (F)	Mid-Point Hardness (DPH)	Surface Hardness (R_c)	Estimated Percent Recrystallization
5	As Received	----	546	52	--
5-1	30	2000	497	48.9	5
5-2	30	2100	488	48.3	5
5-3	30	2200	488	48.3	10
5-4	30	2300	476	47.5	15
5-5	30	2400	467	46.8	20
5-6	30	2500	409	41.7	80
5-7	30	2600	375	38.3	90

TABLE IV

HARDNESS AND PERCENT OF RECRYSTALLIZATION
OF 0.020-INCH THICK TUNGSTEN SHEET

Specimen Number	Time at Temperature (min)	Temperature (F)	Mid-Point Hardness (DPH)	Surface Hardness (R_c)	Estimated Percent Recrystallization
6	As Received	----	534	51.3	--
6-3	30	2200	480	47.6	10
6-4	30	2300	470	46.8	10
6-5	30	2400	450	45.3	15
6-6	30	2500	467	46.8	50
6-7	30	2600	442	44.6	70
6-8	30	2700	395	40.3	100
6-9	30	2800	370	37.7	100

TABLE V

HARDNESS AND PERCENT OF RECRYSTALLIZATION
OF 0.060-INCH THICK TUNGSTEN SHEET

Specimen Number	Time at Temperature (min)	Temperature (F)	Mid-Point Hardness (DPH)	Surface Hardness (R_c)	Estimated Percent Recrystallization
14	As Received	----	507	49.5	0
14-5	30	2400	447	45.1	40
14-6	30	2500	428	43.5	50
14-7	30	2600	409	40.8	60
14-8	30	2700	372	37.8	100
14-9	30	2800	360	36.6	100

TABLE VI

HARDNESS AND PERCENT OF RECRYSTALLIZATION
OF 0.100-INCH THICK TUNGSTEN SHEET

Specimen Number	Time at Temperature (min)	Temperature (F)	Mid-Point Hardness (DPH)	Surface Hardness (R_c)	Estimated Percent Recrystallization
65	As Received	----	537	51.4	0
65-6	30	2500	430	43.6	40
65-7	30	2600	389	39.8	60
65-8	30	2700	350	35.5	100
65-9	30	2800	340	34.4	100
65-10	30	2900	330		100

The MAB 192-M specification defines the recrystallization temperature as the minimum temperature at which in one hour the microstructure is 50 percent recrystallized and the decrease in hardness is 2/3 of the total decrease from the wrought condition to the fully recrystallized condition. Based on this definition, the recrystallization temperature for the 0.010-, 0.020-, 0.060-, and 0.100-inch thick tungsten sheet is 2450 F, 2500 F, 2525 F, and 2550 F, respectively. The effect of temperature and time at temperature on the recrystallization of 0.020-inch thick tungsten sheet is shown in Figure 3. The microstructures obtained are representative of the sheet at the temperature indicated.

2.1.4 BEND TRANSITION TESTS

Bend tests were conducted on the remaining four sheet gages to determine the bend transition temperature between individual sheets within each sheet gage in the longitudinal and transverse directions.

The procedures and equipment used for the determination of the bend transition temperature parameters were discussed in detail in Reference 1. In addition, the results of the first series of bend test evaluations for both the longitudinal and transverse directions of the four tungsten sheet gages were presented. The test specimens were prepared by hot shearing strips from the sheet stock. After cutting, longitudinal and transverse bend specimens were degreased, alkaline cleaned, acid pickled, rinsed,

As-Received
Sheet No. 6
Transverse
DPH 525

As-Received
Sheet No. 6
Longitudinal
DPH 534

SHEET # 5 - 0.010 INCH
SHEET # 6 - 0.020 INCH
SHEET #14 - 0.060 INCH
SHEET #65 - 0.100 INCH

ESTIMATED PERCENT RECRYSTALLIZATION

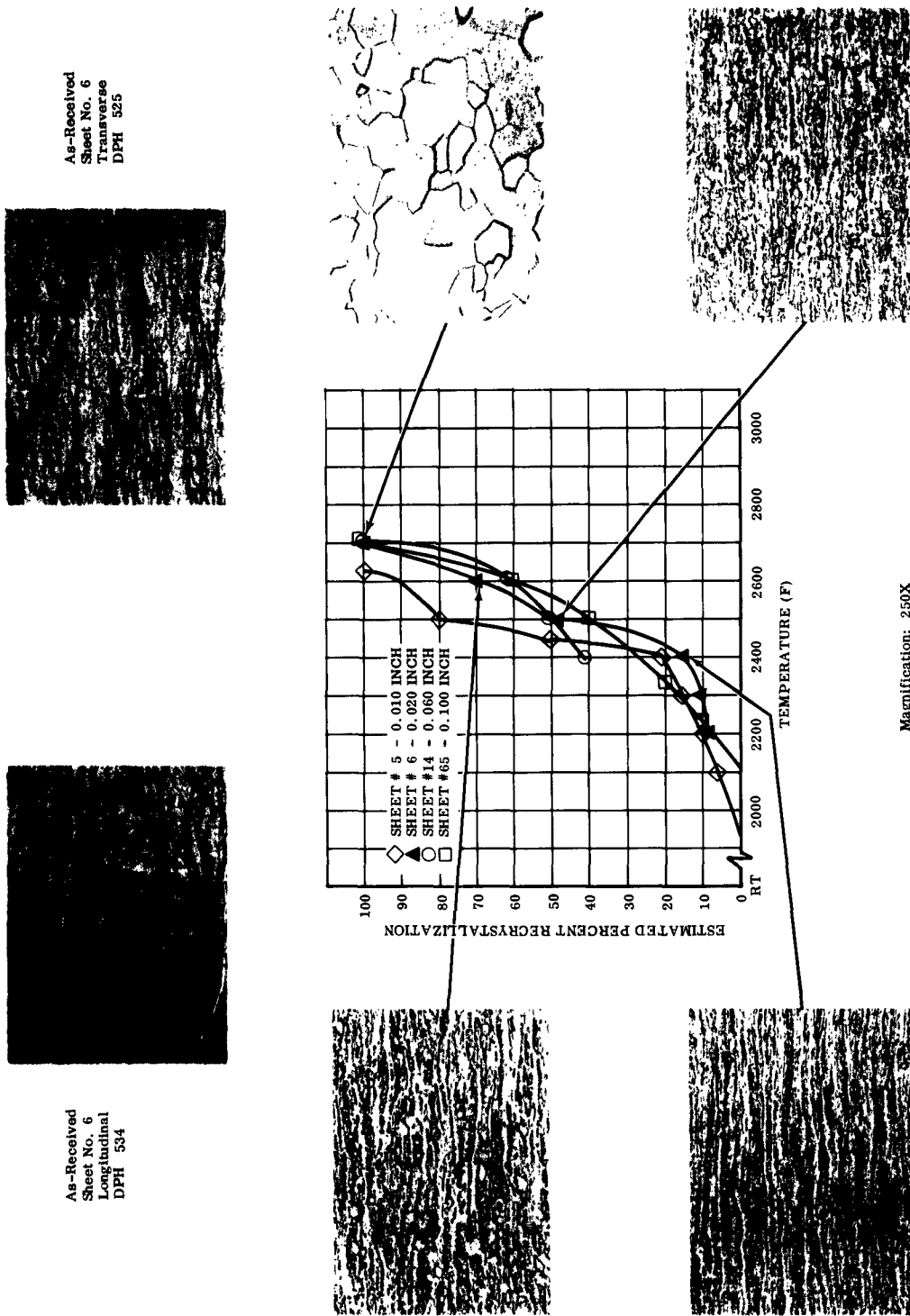TEMPERATURE (F)

Magnification: 250X

FIGURE 3.   EFFECT OF TEMPERATURE AND TIME AT TEMPERATURE ON
RECRYSTALLIZATION OF TUNGSTEN

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and oven dried to remove the surface scale from the hot shearing operation. The sheared edges were ground with a rubber bonded grinding wheel and manual polishing of the edges, in the longitudinal direction, with number 1 and number 0 emery paper removed any edge defects. The edges of each specimen were examined under 10 X magnification for cracks, burrs, or notches.

The bend transition temperature tests were conducted with a 5T radius punch for all thicknesses except for the 0.010 material, for which a 6T radius punch was used. During the March 1964 meeting, the MAB, RMSRP subpanel suggested that any future bend transition evaluations will be conducted with a 4T radius punch, which is generally used in the refractory metals industry, although the MAB 192-M specification does not specify a particular radius punch be used. The ram speed used to bend the tungsten sheet specimens was 1 inch per minute and the loads were measured directly from the machine. The test temperature was thermostatically controlled by an immersion thermocouple in contact with the surface of the specimen. Bend tests to 500 F were conducted in a bath of high flash point mineral oil. At temperatures above 500 F, a potassium nitrate-sodium nitrite salt bath was substituted for the mineral oil.

Figure 4 shows a typical bend test specimen being lowered into a salt bath. The sample and fixture are held in heated bath for 3-5 minutes to allow for temperature stabilization prior to actual testing.

The transition temperature ranges for the tungsten sheet specimens, cut in the longitudinal and transverse directions, are summarized in Table VII. These ranges are based on the minimum temperature at which a 90-degree to 105-degree bend was achieved, and the maximum temperature at which fracture occurred before a 90-degree bend was accomplished. The data in Table VII indicate that the material with the greatest amount of cold work has the lowest transition temperature and the materials with lesser degrees of cold work exhibited higher bend transition temperatures. The tested specimens are shown in Figure 5.
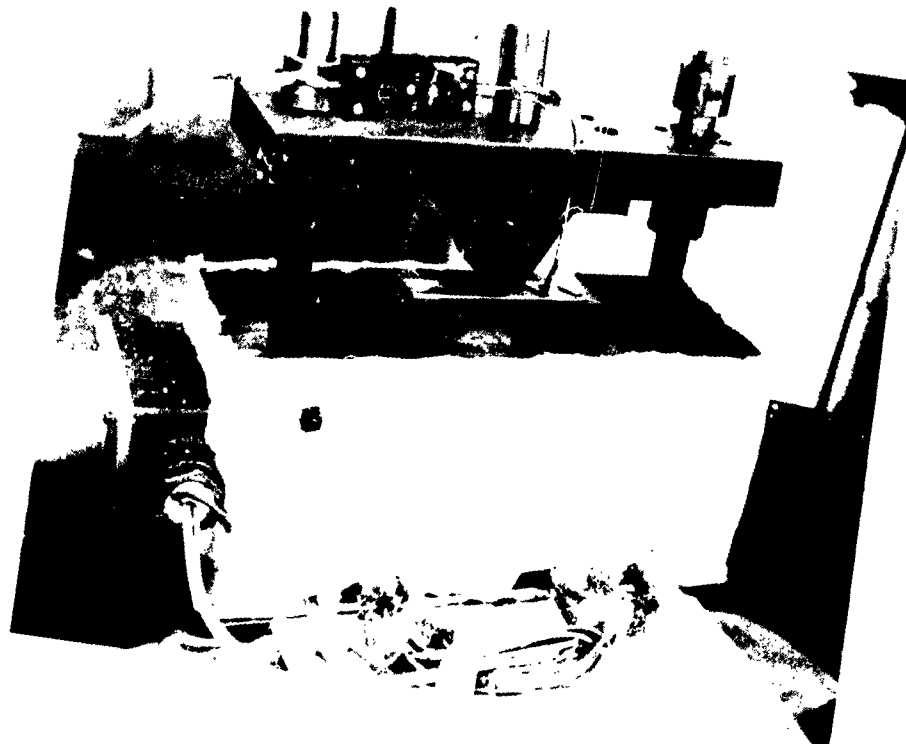
FIGURE 4. HEATING OF BEND TEST SPECIMEN IN SALT BATH

In the bend tests with the 0.010-inch material, the 6T transition temperature was approximately 50 degrees F lower in the longitudinal direction than in the transverse direction. In the bend tests with 0.020-, 0.060-, and 0.100-inch sheet material, the 5T transition temperature was 40 degrees F to 220 degrees F lower in the longitudinal direction than in the transverse direction. Graphic representations of the bend transition temperature data for tungsten sheet specimens in transverse and longitudinal direction given in Figures 6 through 9.

At the request of the MAB, RMSRP subpanel, the specimens that were initially bent 90 degrees to 105 degrees were reverse flattened using the equipment shown in Figure 10. This severe flattening was to detect delamination tendencies in the various sheet gages. The reverse bend evaluation was conducted with a ram speed of 1 inch per minute at temperatures slightly higher than previous single bend tests. The results of the reverse bend tests indicated that the 0.010-inch transverse and longitudinal oriented material exhibited a lesser tendency to delaminate and crack than the other

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TABLE VII

RESULTS OF DUCTILE-BRITTLE TRANSITION BEND TESTS

Sheet Number	Sheet Thickness (in.)	Test Direction	Ductile Temperature (F)	Brittle Temperature (F)	Load (lb)	Remarks
8	0.010	Longitudinal	96	---	50	
8	0.010	Longitudinal	---	78	21	
8	0.010	Transverse	98	---	40	
8	0.010	Transverse	---	78	45	
9	0.010	Longitudinal	62	---	50	
9	0.010	Longitudinal	---	40	35	
9	0.010	Transverse	150	---	46	
9	0.010	Transverse	---	100	12	
10	0.010	Transverse	96	---	46	
10	0.010	Transverse	---	82	43	
10	0.010	Longitudinal	82	---	45	
10	0.010	Longitudinal	---	64	47	
12	0.010	Transverse	96	---	46	
12	0.010	Transverse	---	82	43	
12	0.010	Longitudinal	78	---	32	
12	0.010	Longitudinal	---	62	30	
13	0.010	Longitudinal	10	---	52	
13	0.010	Longitudinal	---	<10	---	Ran out of test specimens
13	0.010	Transverse	78	<40	42	Ran out of test specimens
14	0.010	Transverse	14	---	52	
14	0.010	Transverse	---	<10	---	Ran out of test specimens
14	0.010	Longitudinal	78	---	32	
14	0.010	Longitudinal	---	62	40	
2-1	0.020	Longitudinal	150	---	46	
2-1	0.020	Longitudinal	---	130	62	
2-1	0.020	Transverse	260	---	52	
2-1	0.020	Transverse	---	250	55	
4-1	0.020	Transverse	200	---	30	
4-1	0.020	Transverse	---	175	45	
4-1	0.020	Longitudinal	150	---	46	
4-1	0.020	Longitudinal	---	82	49	
4-2	0.020	Longitudinal	150	---	40	
4-2	0.020	Longitudinal	---	120	42	
4-2	0.020	Transverse	240	---	55	
4-2	0.020	Transverse	---	220	60	
3	0.060	Transverse	460	---	315	
3	0.060	Transverse	---	440	350	

TABLE VII (Cont)

RESULTS OF DUCTILE-BRITTLE TRANSITION BEND TESTS

| Sheet Number	Sheet Thickness (in.)	Test Direction	Ductile Temperature (F)	Brittle Temperature (F)	Load (lb)	Remarks
3	0.060	Longitudinal	300	---	340	
3	0.060	Longitudinal	---	280	300	
7-C	0.060	Longitudinal	360	---	275	
7-C	0.060	Longitudinal	---	330	290	
7-C	0.060	Transverse	580	---	295	
7-C	0.060	Transverse	---	560	280	
10	0.060	Transverse	520	---	280	
10	0.060	Transverse	---	480	290	
10	0.060	Longitudinal	400	---	265	
10	0.060	Longitudinal	---	390	300	
14	0.060	Longitudinal	570	---	340	
14	0.060	Longitudinal	---	560	345	
14	0.060	Transverse	770	---	250	
14	0.060	Transverse	---	700	265	
48	0.100	Transverse	680	---	525	
48	0.100	Transverse	---	660	510	
48	0.100	Longitudinal	640	---	465	
48	0.100	Longitudinal	---	560	468	
49	0.100	Transverse	500	---	572	
49	0.100	Transverse	---	480	590	
49	0.100	Longitudinal	500	---	600	
49	0.100	Longitudinal	---	430	432	
51	0.100	Transverse	520	---	590	
51	0.100	Transverse	---	500	590	
51	0.100	Longitudinal	480	---	520	
51	0.100	Longitudinal	---	450	552	
58	0.100	Transverse	460	000	472	
58	0.100	Transverse	---	450	540	
58	0.100	Longitudinal	370	---	560	
58	0.100	Longitudinal	---	350	630	
61	0.100	Transverse	500	---	600	
61	0.100	Transverse	---	480	630	
61	0.100	Longitudinal	380	---	680	
61	0.100	Longitudinal	---	350	700	
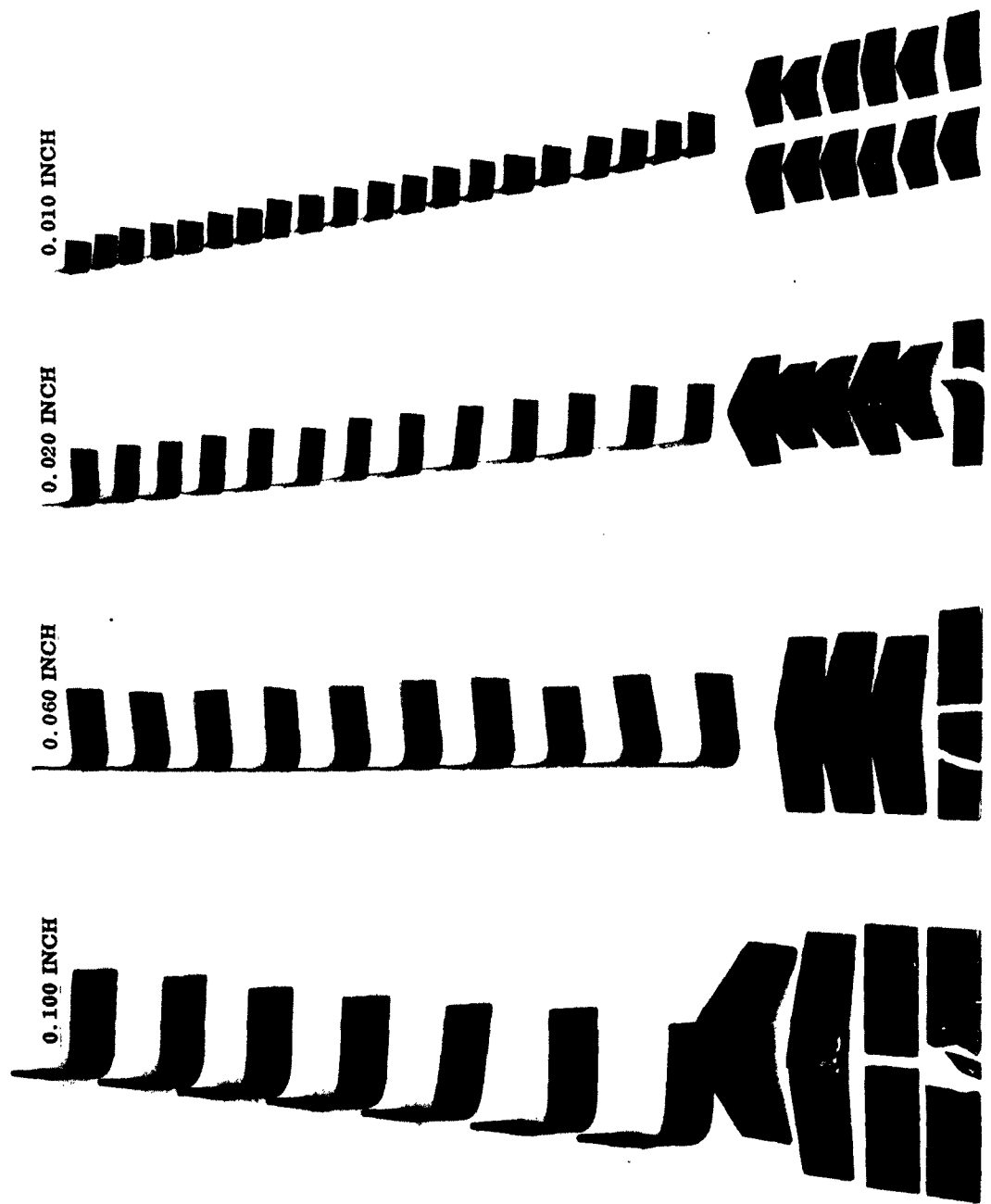
FIGURE 5. RESULTS OF BEND TRANSITION TEMPERATURE DETERMINATIONS
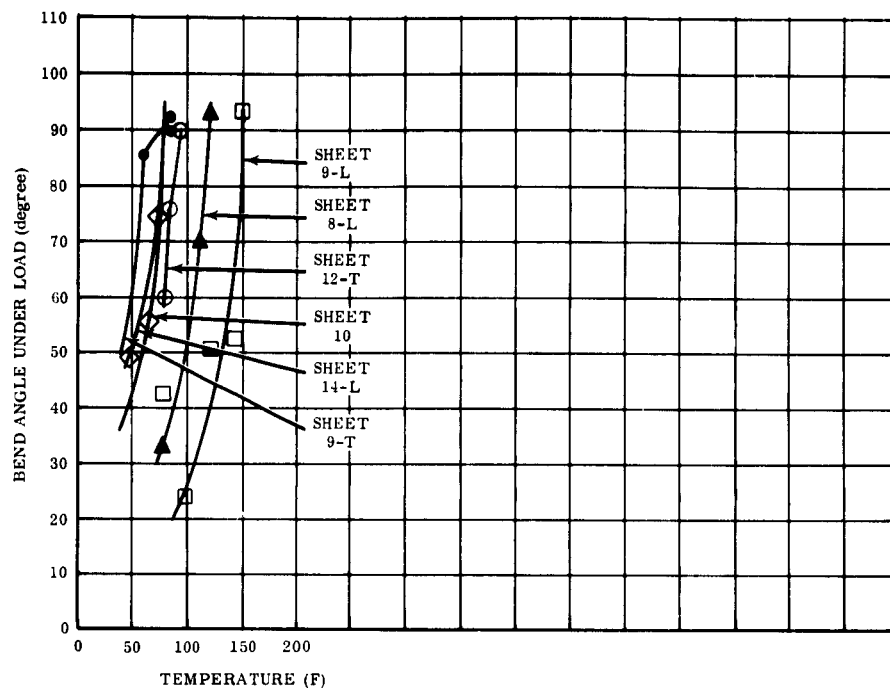
18

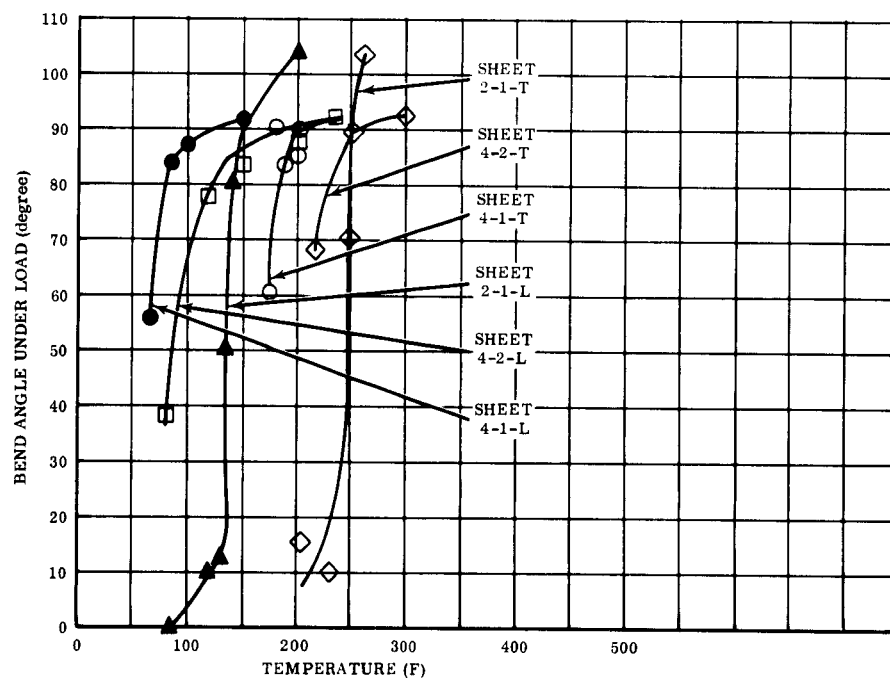FIGURE 6. BEND TRANSITION TEMPERATURE CURVES; 0.010-Inch Tungsten

FIGURE 7. BEND TRANSITION TEMPERATURE CURVES; 0.020-Inch Tungsten
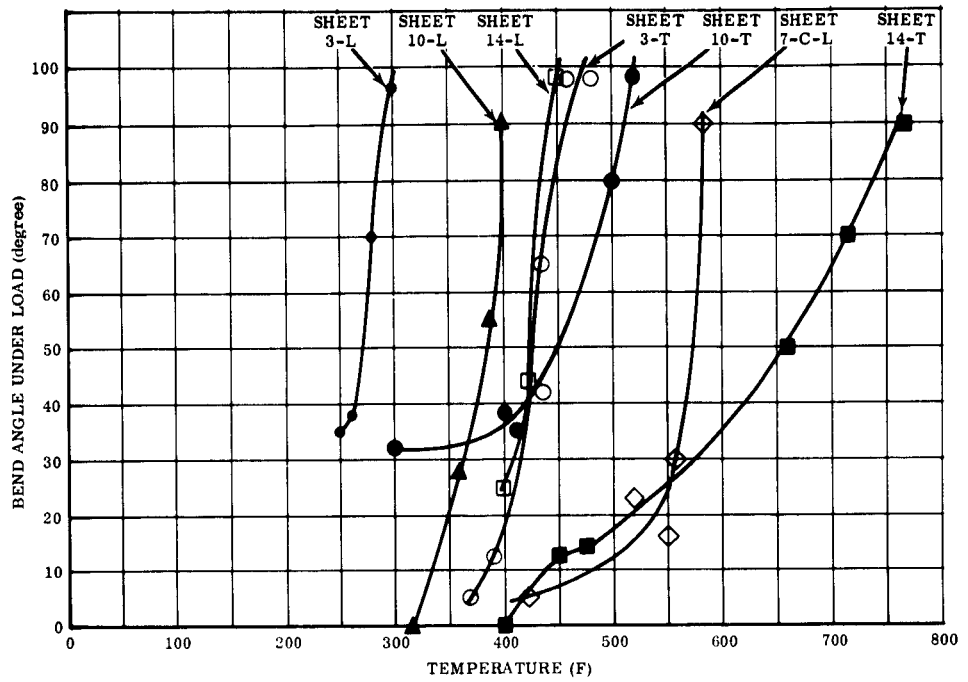
19

FIGURE 8. BEND TRANSITION TEMPERATURE CURVES; 0.060-Inch Tungsten
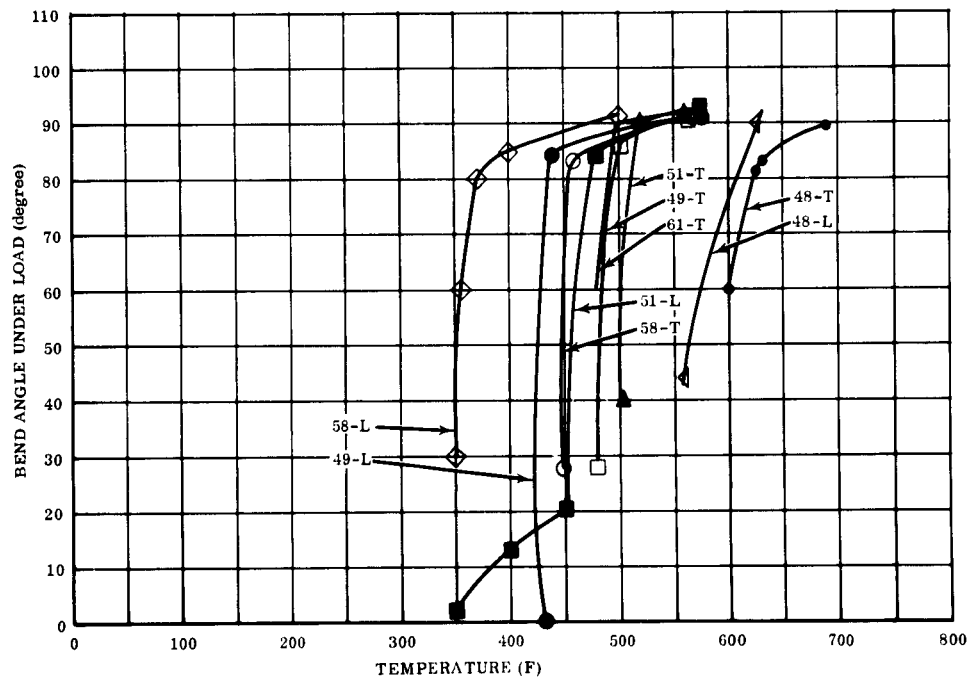

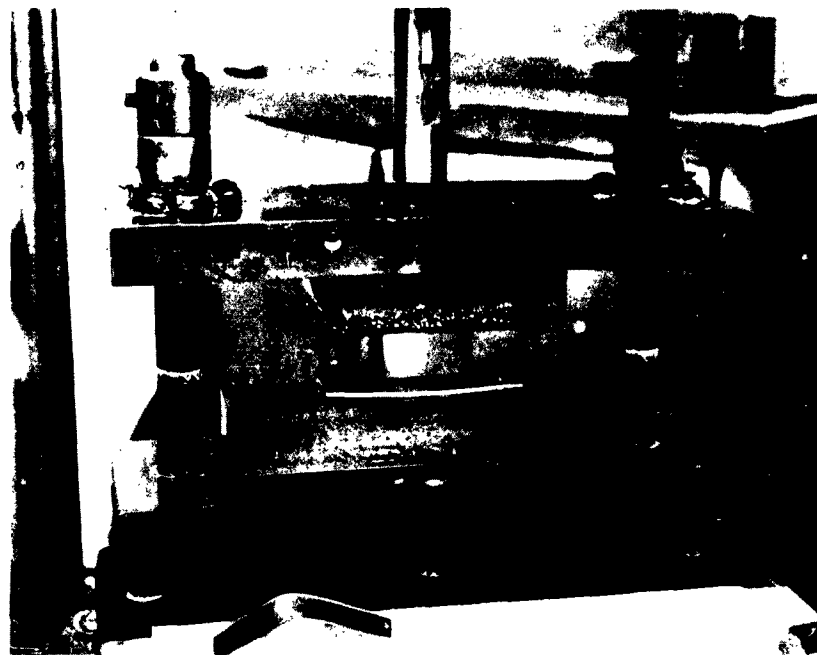FIGURE 9. BEND TRANSITION TEMPERATURE CURVES; 0.100-Inch Tungsten

20

FIGURE 10. REVERSE BENDING TEST FIXTURE

sheet gages. As the sheet thickness increased, it was found that the failures pre-
dominately occurred from internal delaminations in the thickness direction. Only
the 0.020-inch test samples showed a combination of internal delaminations and sur-
face cracking at the root area. This phenomenon occurred in the longitudinal and
transverse directions, in a random fashion. Observation of the reverse bending
process on the 0.060- and 0.100-inch specimens indicated either complete failure
when reverse flattened, or the material was satisfactorily bent flat. The 0.100-inch
material showed a pronounced tendency toward hairline delaminations propagating
almost the full length of the specimen. The 0.060-inch material showed less tendency
to propagate hairline delaminations during reverse bending. The results of reverse
bending of several gages of tungsten sheet are shown in Figures 11 and 12.

Previous bend test data showed that the bend transition temperature was the
lowest for the sheets with the highest percentage of cold work, and the highest for the
least cold work. The relationship also held for reverse bend testing, although the
transition temperatures were from 150 degrees F to 250 degrees F higher than those
measured in the single bend tests.
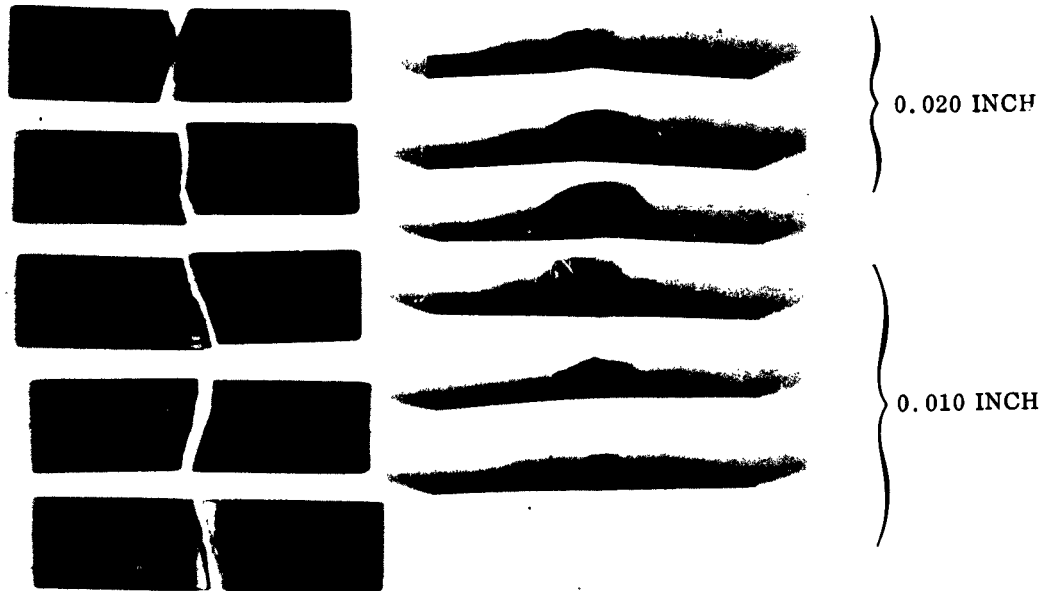
0.020 INCH

**FIGURE 11. RESULTS OF REVERSE BENDING EVALUATIONS; 0.010- and 0.020-Inch Tungsten**

0.060 INCH   0.100 INCH

FIGURE 12. RESULTS OF REVERSE BENDING EVALUATIONS; 0.060- and 0.100-inch Tungsten

To determine the amount of strain imposed on the four sheet gages when singly bent with a 5T and 6T punch radius, calculations were made to ascertain the total unit strain. As a direct approximation in determining these strains, several assumptions were made:

1. The total strain is independent of temperature.
2. C_L is inextensible.
3. $Ec = Et$
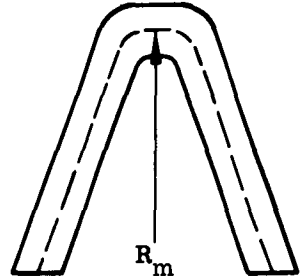
Therefore:

$$\epsilon = \frac{l_o - l_c}{l_c} = \text{total unit strain}$$

$$= \epsilon_E + \epsilon_P$$

$$l_c = 2\pi R_m$$

$$l_o = 2\pi(R_m + \frac{t}{2})$$

$$= 2\pi R_m + \pi t$$

$$\epsilon = \frac{2\pi R_m + \pi t - 2\pi R_m}{2\pi R_m}$$

$$= \frac{t}{2R_m}$$

For $R_m = 5t$

$$\epsilon = \frac{t}{10t}$$

$$\epsilon = 0.1 \text{ inch/inch}$$

For $R_m = 6t$

$$\epsilon = \frac{t}{12t}$$

$$\epsilon = 0.083 \text{ inch/inch}$$

The total unit strain is almost entirely plastic. Depending on F_{ty} and E, the elastic strain will vary from 0.001 to 0.005 inch/inch.

It appears that during initial bending, the plastic strains induced in the tension fibers on the outer surface result in a permanent set. When bending is reversed, compression yielding cannot occur sufficiently in the outer fibers, resulting in a surface which tends to buckle. This buckling is resisted by the tensile stresses across the thickness of the specimen and as reverse bending continues, the thickness tensile stresses exceed the load carrying ability of the tungsten sheet and gross delaminations occur in the weakest thickness plane. Apparently, any decrease in the amount of reduction or pancaking of the grain during rolling will result in increased ductility normal to the rolling plane, but the ductility parallel to the rolling plane will decrease.

III. FORMABILITY STUDIES

The prime objectives of the formability program are to evaluate the various thicknesses of RMSP tungsten sheet material and to compare it with other commercially available grades of tungsten sheet. The formability tests were designed with two objectives:

- Evaluate quality of sheet
- Establish useful forming techniques

Nine different forming techniques will be evaluated to determine the forming characteristics of the four thicknesses of tungsten sheet. The formability limits will be determined for the applicable forming tests and these data will be used to compare materials. This section covers several of the forming methods studied during this reporting period.

Prior to conducting the formability evaluation on the four thicknesses of tungsten sheet material, a number of sheets were selected by random sampling in accordance with the formability sampling plan depicted in Figure 13. This sampling plan accurately shows the location of the test specimens used to establish baseline forming data during the forming evaluation of the tungsten sheet. All of the test samples required for the forming study were hot sheared from each gage of material. To minimize confusion with respect to the sheet rolling direction, lines were scribed on each specimen indicating the grain orientation. The as-sheared forming test material was alkaline-caustic cleaned and acid pickled to remove the surface oxides and scale from heating during shearing operation. After cleaning, the sheet edges were ground on a rubber bonded grinding wheel to remove edge defects.

3.1 BLANKING EVALUATION

A study was conducted on the four gages of tungsten sheet to determine blanking parameters and best temperature range required to produce 2-inch diameter circular blanks. Several sheets from each gage of material was selected at random from each thickness of material. The tungsten sheet was blanked on a 70-ton Minster crank
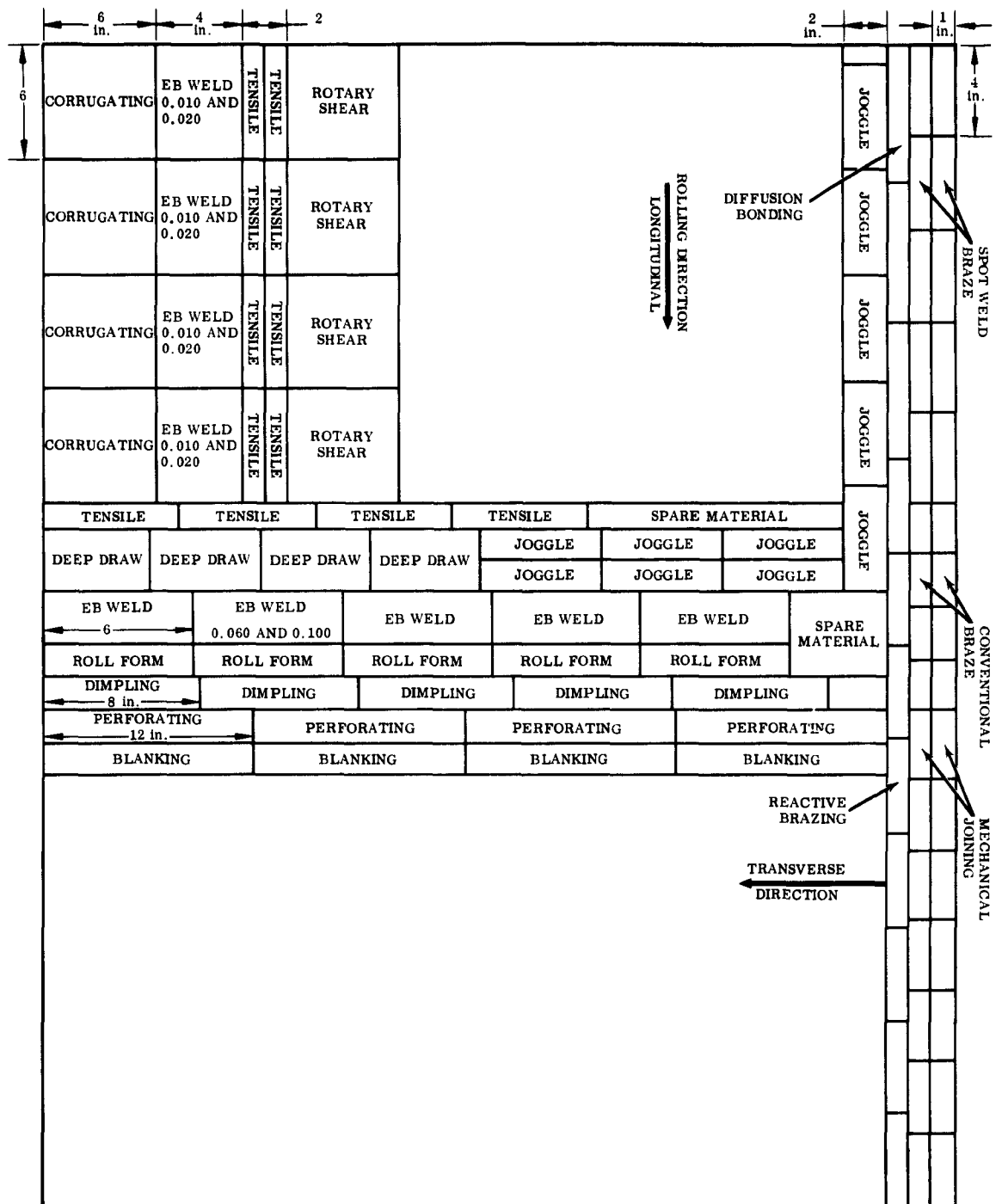
FIGURE 13. TUNGSTEN SHEET FORMABILITY SAMPLING PLAN

press. All blanks were formed with a ram stroke of 11.250 inches and a mean impact velocity of 4.5 inches per second. The mean velocity is based on the total travel of the crank divided by the measured time to impact. It is assumed that the load resistance of the tungsten sheet being blanked to the total force of the crank press is negligible; this velocity also represents rate of blanking.

The starting sheet blanks were hot sheared to 3-inch by 12-inch strips. The sheet blanks were subsequently alkaline-caustic cleaned, followed by acid pickling to remove the surface scale and oxides.

The punches and dies used in this evaluation were made from hot work tool steels with precision ground surfaces. The clearance between the punch and die was 0.003-inch and 0.006-inch, respectively. In general blanking practice (Ref. 4), the clearance normally used is 3 percent of the metal clearance and the common values are between 3 and 10 percent of the metal thickness regardless of the metal and its temper.

All of the sheet materials used in this evaluation were heated with an oxy-acetylene torch, and a surface contact pyrometer was used to measure temperatures to 800 F. Above 800 F, the temperatures were measured with a series of Tempil-stiks, graduated in 100 degree F increments. The sheet temperatures, time to position blanks on the dies, and temperature losses were all determined prior to blanking. It required approximately seven seconds to position the blanks on the die and the temperature drop varied from 20 degrees F per second for the 0.010-inch sheet to 10 degrees F per second for the 0.100-inch sheet. To compensate for the temperature drop, the sheet material was heated from 70 degrees F to 150 degrees F over the particular test temperature. The punch face and die edges were given a thin film of Molykote lubricant to minimize die wear. A rubber stripper with an asbestos liner was used to strip the punch from the sheet blank for the 0.010-, 0.020-, and 0.060-inch material. For the 0.100-inch material, a mechanical stripper was used exclusively due to the higher temperatures involved. The punch and die setup with the rubber stripper and asbestos liner in position is shown in Figure 14. The 0.010- and 0.020-inch sheet blanks were initially blanked with the die having the 0.006-inch clearance. However, it was observed that metals with limited ductility such as tungsten, intermediate clearances produce very rough edges consisting partly of a dull sheared portion and partly of a turned over and burnished lip or burr. The wider
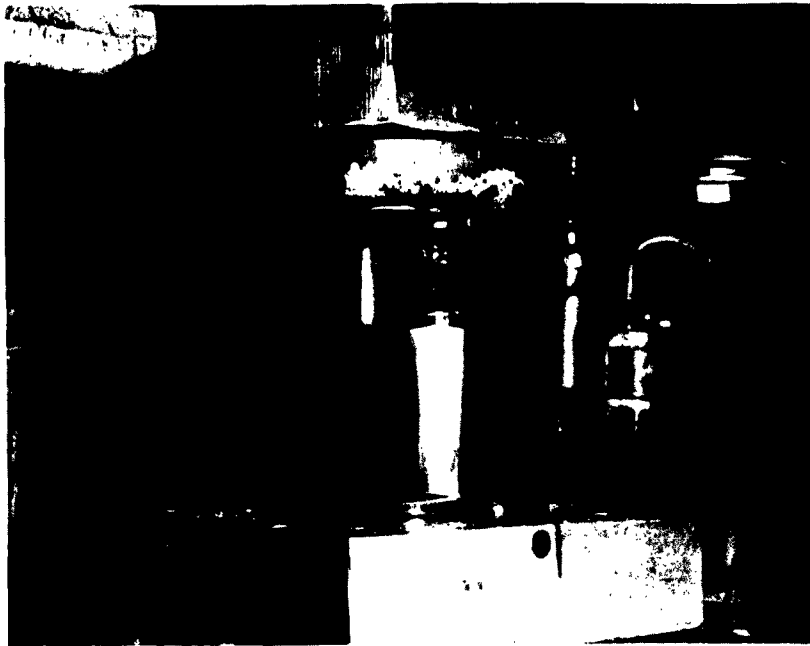
FIGURE 14. PUNCH AND DIE SETUP FOR BLANKING EVALUATION OF TUNGSTEN

clearance also resulted in a number of blanks with delaminations propagating radially
in the upper third, or across the mid-thickness of the material. The number of de-
laminations decreased considerably when the die with the 0.003-inch clearance was
used. The 2-inch diameter blanks did not exhibit the dull shear surface, a burnished
lip, or burr. Based on the 0.003-inch gap distance between the punch and die, the
clearance for the 0.010- and 0.020-inch sheet amounted to 30 percent and 15 percent,
respectively. All parts were blanked in one stroke and no reheats were necessary to
complete the blanking operation. The minimum temperature at which successful
blanking of the 0.010- and 0.020-inch tungsten sheet occurred, without any evidence
of edge defects as determined by microscopic and die penetrant inspection, was found
to be 400 F and 480 F for the 0.010- and 0.020-inch sheets, respectively.

The 0.060- and 0.100-inch sheets were blanked with the punch and die with
the 0.006-inch gap clearance. Depending on the metal thickness, this corresponds to
a gap clearance of 10 percent and 6 percent, respectively. Blanking at elevated tem-
peratures with the 0.006-inch gap clearance resulted in satisfactory 2-inch diameter

blanks without any noticeable burrs or burnished lips on the blanked specimens. However, after several blanking operations at temperature, the punch and die had to be reground due to the rapid wearing of the cutting edges even though Molykote was used as a die lubricant. The punch about to impact and blank an 0.060-inch sheet specimen is shown in Figure 15 and Figure 16 shows a 0.100-inch thick blank sample on a tray with the punch nearly bottomed in the die. The microstructure of a 0.020- and 0.060-inch specimen that were blanked at 500 F and 800 F, respectively, is shown in Figure 17. The structures show a localized plastically deformed region where the grains are compressed by the action of the punch and die. No failures or defects were found in either specimen.

The minimum temperature at which satisfactory 2-inch diameter blanks were obtained on 0.060- and 0.100-inch tungsten sheet was found to be 700 F and 1050 F, respectively. The minimum blanking temperatures for the four gages of tungsten is graphically presented in Figure 18. The upper temperature limits do not necessarily indicate the maximum temperatures, but only tend to illustrate where no further improvement in blanking occurs, all other conditions being equal. The results of blanking the four gages of tungsten sheet are shown in Figure 19.

Although the force required to blank each gage of sheet material could not be readily determined in the specific equipment used, tensile tests in the four sheet gages were conducted within the temperature range in which satisfactory blanking was achieved. The total force required for blanking each sheet was calculated from part geometry, and the ultimate tensile strength of tungsten at blanking temperature. The shear strength of tungsten was assumed to be approximately 60 percent of its F_{tu} at temperature. The results are as follows:

Blank diameter = 2-inches
Assume shear strength for tungsten = 60 percent of F_{tu}

0.010 inch

F_{tu} = 159.6 ksi at 400 F

60 percent shear strength

    = 95,500 psi

    = 95,500 x 0.063

    = 6250 psi

$A = \pi \times d \times t$

    = 3.14 x 2 x 0.010

    = 0.063

0.020 inch

F_{tu} = 129.0 ksi at 600 F

60 percent F_{tu}

    = 77,400 psi

    = 77,400 x 0.126

    = 9750 psi

$A = \pi \times d \times t$

    = 3.14 x 2 x 0.020

    = 0.126

0.060 inch

F_{tu} = 106.6 ksi at 800 F

60 percent F_{tu}

    = 64,000 psi

    = 64,000 x 0.377

    = 24,150 psi

$A = \pi \times d \times t$

    = 3.14 x 2 x 0.060

    = 0.377

0.100 inch

F_{tu} = 90.0 ksi at 1200 F

60 percent F_{tu}

    = 54,000 psi

    = 54,000 x 0.628

    = 33,950 psi

$A = \pi \times d \times t$

    = 3.14 x 2 x 0.100

    = 0.628

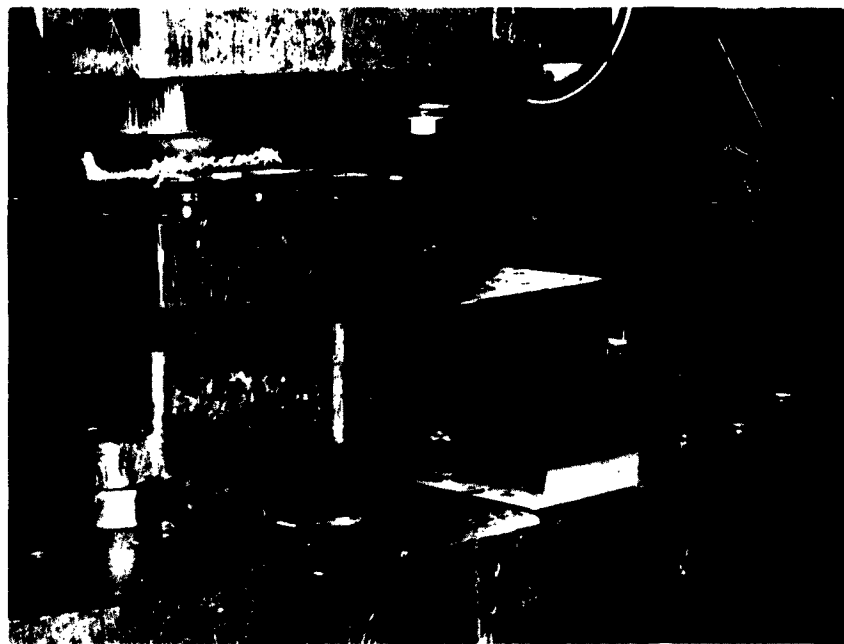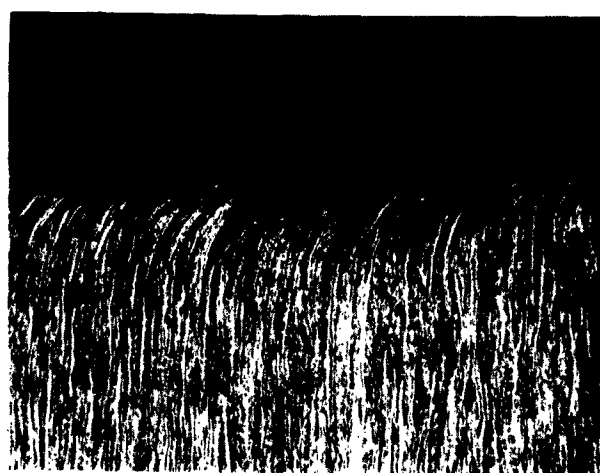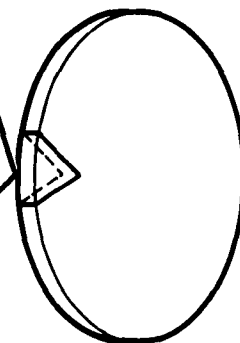FIGURE 15.   BLANKING OF 0.060-INCH TUNGSTEN

FIGURE 16.   FINISHED BLANK OF 0.100-INCH TUNGSTEN

Etch: Murikamis
Magnification: 75X

0.060 inch

BLANKED SURFACE

0.020 inch

Etch: Murikamis
Magnification: 150X

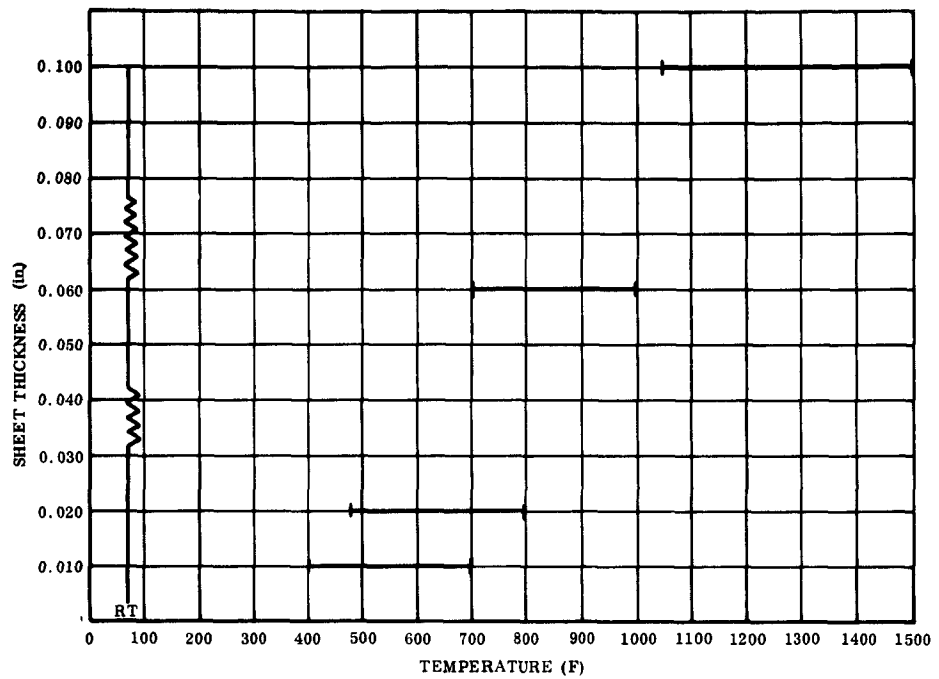FIGURE 17. MICROSTRUCTURES OF BLANKED TUNGSTEN SHEET

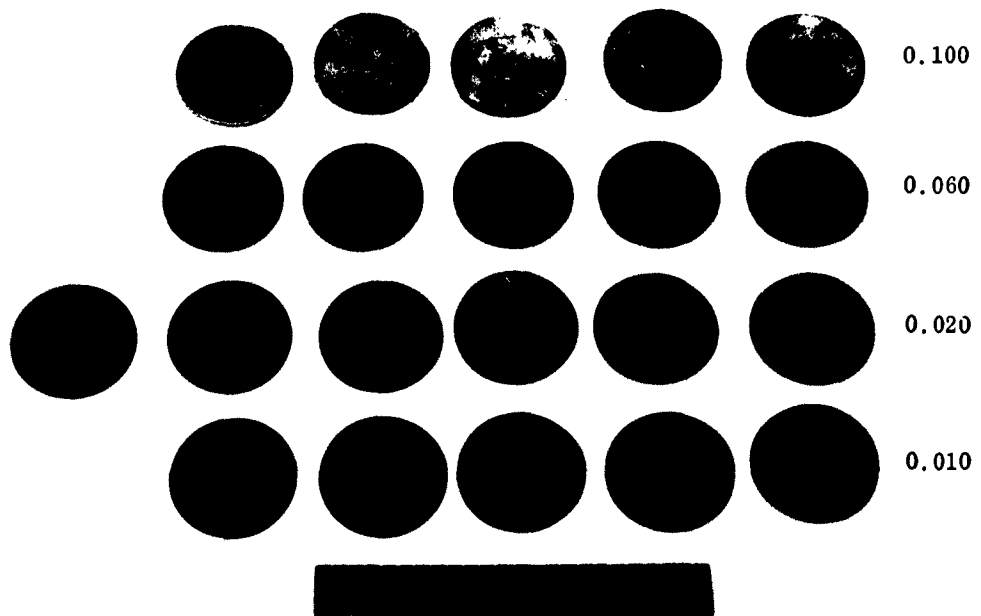FIGURE 18. TEMPERATURE RANGE FOR BLANKING VARIOUS THICKNESSES OF
TUNGSTEN SHEET

FIGURE 19. AS-FORMED BLANKS OF TUNGSTEN

3.2 PERFORATION EVALUATION

An evaluation was conducted on the four thicknesses of tungsten sheet to determine the perforating parameters and range of temperatures required to produce 1/8-, 1/4-, and 1/2-inch diameter perforations. Perforating is the multiple punching of a series of small holes, or contours, in sheet material. Several sheets of each material thickness were selected at random from a specific lot of tungsten sheet. The tungsten sheet was perforated on a 60-ton, clutch-driven, Niagara crank press. All parts were perforated with a ram stroke of 8-1/4 inches and a mean velocity of 3.4 inches per second. The mean velocity is based on the total stroke divided by the average time. It is assumed that the load resistance of the tungsten sheet being perforated to the total force imposed by the crank press is negligible. The perforating blanks were hot sheared strips 3 inches wide by 12 inches long. After shearing, the blanks were chemically cleaned to remove the surface scale and oxides. The punches and dies were fabricated from hot-work, chrome-vanadium tool steels with precision ground surfaces. The clearance between the die and punch for the perforating diameters was 0.004 inch. Each sheet used in this evaluation was heated with an oxyacetylene torch. The temperatures were monitored with an Alnor surface pyrometer up to 800 F and Tempilstiks, graduated in 100 degree F increments, were used to monitor temperatures above 800 F. The time to position blanks on the perforating die, and temperature losses were all determined prior to perforating. It took approximately 5 to 7 seconds to position the hot blank on the die. The drop in temperature was compensated for by heating the material from 70 degrees F to 150 degrees F over the given test temperature. The punch face and die was heated to 240 F to 250 F to minimize the chilling effect on the heated tungsten sheet blanks. The punch had a rubber stripper with an asbestos liner for removing the punch from the perforated blanks. The same type of equipment was used on all four sheet gages and for each of the perforating diameters investigated. A punch perforating a 1/4-inch diameter hole into a sheet of 0.020-inch tungsten is shown in Figure 20 and Figure 21 shows a 0.020-inch tungsten sheet being perforated with a 1/8-inch diameter punch.

During the perforating investigation of the 0.010- and 0.020-inch material, it was observed that the thinner sheet gages exhibited a tendency towards buckling, edge cracking, and brittle fracturing at temperatures below 400 F. At temperatures above 400 F, the sheet material was perforated satisfactorily. No further edge defects
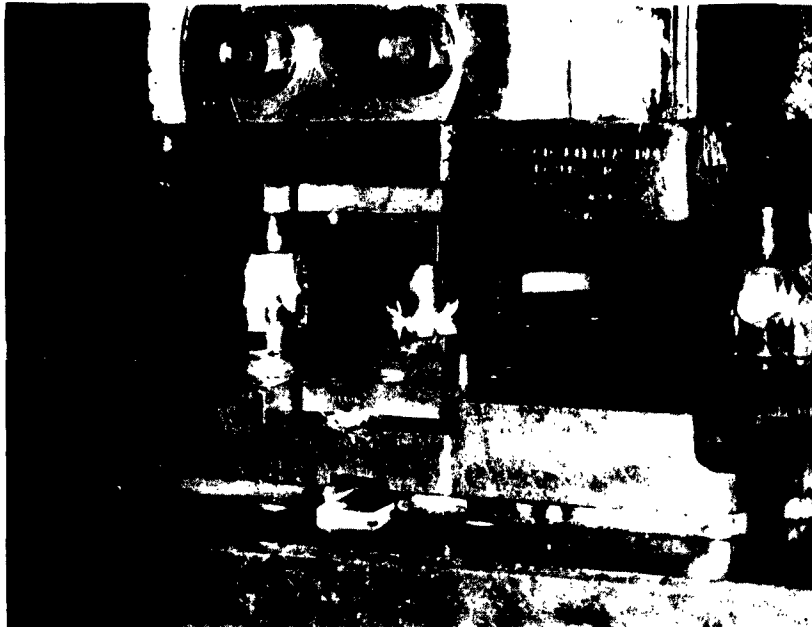
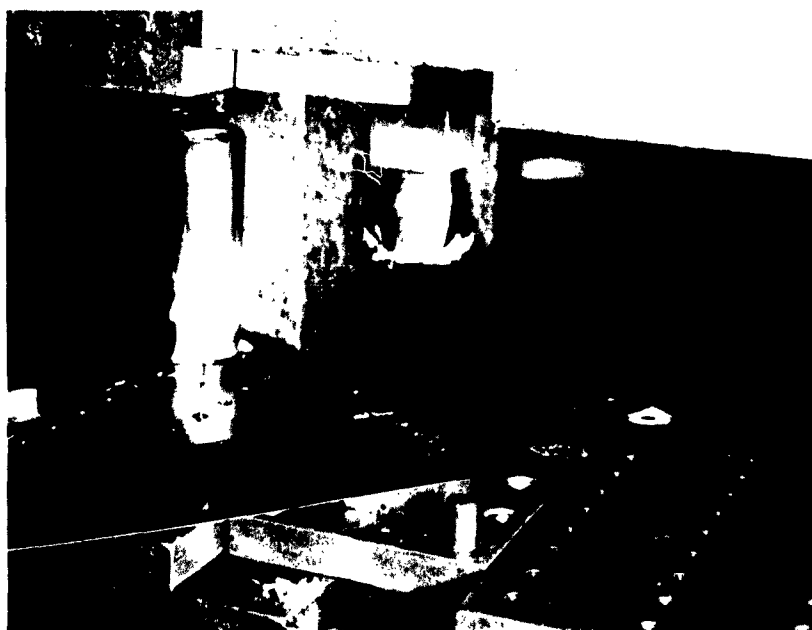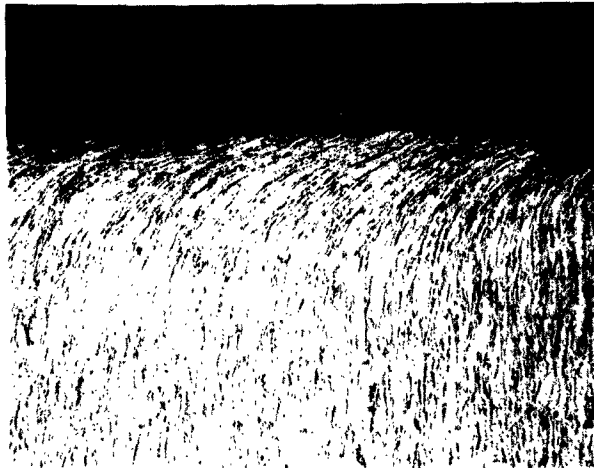FIGURE 20. PERFORATING 1/4-INCH DIAMETER HOLES IN TUNGSTEN SHEET

FIGURE 21. SETUP FOR PERFORATING 1/8-INCH DIAMETER HOLES IN TUNGSTEN SHEET

were found under microscopic and dye penetrant inspection techniques. It was believed the 0.004-inch gap distance between the punch and die should be reduced to 0.001 inch - 0.002 inch to minimize the buckling and edge cracking of the thin gage tungsten sheet. sheet.

The minimum temperature for the successful perforating of the 0.010-inch tungsten sheet was found to be 200 F for the 1/8- and 1/4-inch diameter and 250 F for the 1/2-inch diameter. The minimum temperature for the 0.020-inch sheet was 400 F for the 1/8- and 1/4-inch diameter and 450 F for the 1/2-inch diameter.

The 0.060- and 0.100-inch sheets were also perforated with a punch and die with 0.004-inch gap clearance. It was found that perforating the heavier gage sheet material at elevated temperatures did not result in any buckling or cracked edges, which results from excess gap clearance between the punch and die edges. This evaluation also indicated that it was possible to successfully perforate the 0.060- and 0.100-inch sheet with 1/8- and 1/4-inch diameter punches at temperatures approximately 200 degrees F lower than that for perforating 1/2-inch diameter holes. Microscopic examination of the 0.100-inch perforated blanks at 25X magnification showed slight circumferential discontinuous cracks of what appears to be coining of the top surface approximately 0.040-inch behind the perforated hole. These cracks are believed to be the result of bending the sheet by the punch during the perforating cycle. With materials of limited low temperature ductility like tungsten, the circumferential cracking can be strongly affected by the coining action of the punch and is dependent upon material thickness, perforating temperatures, and type of punch and die used. These effects were observed on 0.060-inch material perforated at temperatures below 450 F and on 0.100-inch material perforated at temperatures below 600 F. Above these temperatures, this particular effect was not found on any 0.060- and 0.100-inch sheet blanks. The minimum temperature for successful perforating 1/8- and 1/4-inch diameter holes in 0.060-inch material was 400 F and for 1/2-inch diameter holes, 600 F. The minimum temperature for successful perforating 1/8- and 1/4-inch diameter holes in 0.100-inch material. The microstructure of a 1/2-inch diameter perforation at 650 F in a sheet of 0.100-inch tungsten is shown in Figure 22.

PERFORATING DIRECTION➡

ETCH: Murikamis

Magnification: 75X

FIGURE 22. MICROSTRUCTURE OF 0.100-INCH TUNGSTEN; Perforated at 650 F

The temperature range for perforating the 1/8-, 1/4-, and 1/2-inch diameter holes on the four gages of tungsten sheet is shown in Figures 23 through 25. The temperatures shown on the graphs reflect the range of temperatures investigated. Temperatures above those shown revealed no significant improvement in perforating 1/8-, 1/4-, and 1/2-inch holes in tungsten sheet. The results of the various perforating diameters attempted on the four gages of tungsten sheet are shown in Figure 26.

3.3 DEEP DRAWING EVALUATION

Preliminary investigations were made to determine the feasibility of producing deep drawn or deep recessed shapes using conventional shop practices and tooling. The primary objective of this study was to evaluate the formability parameters for the deep drawing or recessing of tungsten sheet under various forming conditions. A 1.75-inch diameter hemisphere was chosen as the initial test shape, with the preliminary evaluation to be conducted with 0.060- and 0.100-inch tungsten sheet.
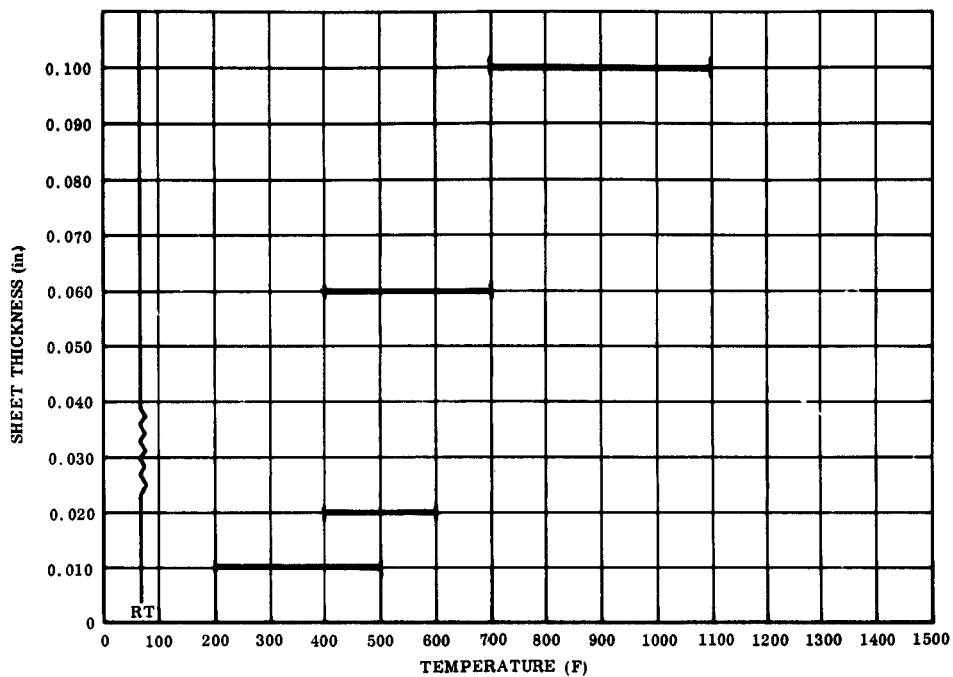
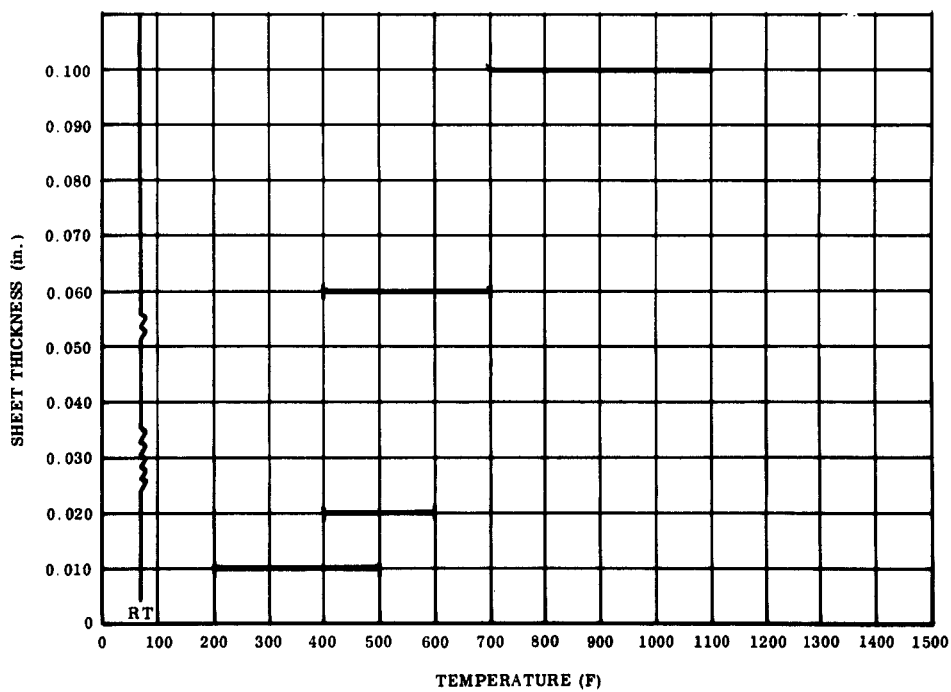FIGURE 23. TEMPERATURE RANGE FOR PERFORATING 1/8-INCH DIAMETER TUNGSTEN

FIGURE 24. TEMPERATURE RANGE FOR PERFORATING 1/4-INCH DIAMETER TUNGSTEN
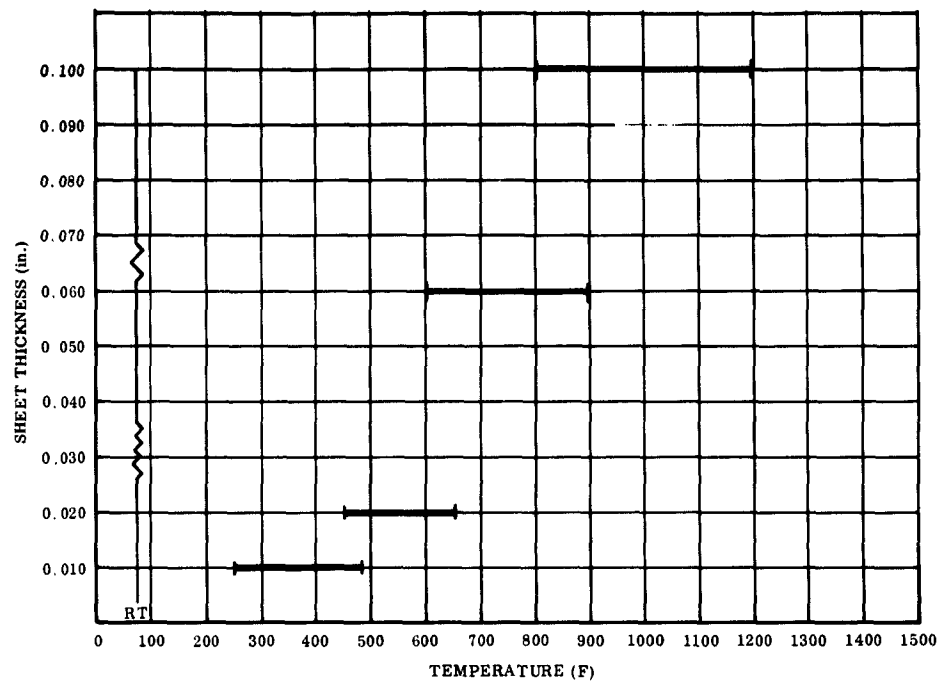
38

FIGURE 25.   TEMPERATURE RANGE FOR PERFORATING 1/2 -INCH DIAMETER
TUNGSTEN

FIGURE 26.   PERFORATED TUNGSTEN SHEETS

A Kirksite (zinc-aluminum alloy) drop hammer punch and a die with a 0.875-inch radius was designed to permit the use of a draw ring if the initial tests prove this was a feasible approach for deep drawing small-radius hemispheres. Locating pins were incorporated in the Kirksite die to provide for accurate positioning of the draw blank.

Four 6-inch square by 0.060-inch thick blanks were circle sheared to approximately 5-1/2-inches in diameter. The edges of the circular blanks were ground on a rubber bonded grinding wheel to remove any edge defects or work hardening effects from the circular shearing. The test blanks were alkaline-caustic cleaned and acid pickled to remove scale and surface oxides. The blanks were cut slightly oversize to prevent edge wrinkling during deep drawing and to simplify the rapid removal from the Kirksite die after drawing was completed. Since Kirksite is a low melting, zinc-base alloy, the heated tungsten sheet could not remain in contact with the die surface for more than a few seconds or surface melting of the die would occur. The punch and die was mounted on a drop hammer press and the 0.060-inch circular tungsten sheet blanks were heated with an oxyacetylene torch to 1200 F to 1300 F. The temperatures were monitored with Tempilsticks graduated in 100 F increments. The heated blank was transferred to three support springs which held the heated blank 3/4 inch above the die cavity. The blanks were then reheated to 2100 F and were immediately formed. Evaluation of the first deep drawn part showed that the blank had four splits, 90 degrees apart, in the cup area of the blank. Because of the rapidity of the forming operation, the Kirksite die and punch did not show any evidence of damage from the deep drawing of heated tungsten sheet. Since failure occurred on the first blank, the forming of the second blank was done in a two-stage operation. The second blank was deep drawn with two hammer blows, with an intermediate reheat after the first blow. The second blank was formed in this manner and again the blank failed in the cup area. No tool damage was experienced with this modified forming procedure. Edge wrinkling was negligible on the second blank.

A third 0.060-inch thick blank was deep drawn in three progressive stages by reheating to 2100 F before each strike with the drop hammer. The deep drawn part again failed in the cup area on the last strike. The part was approximately 75 percent complete when failure occurred. Again, it was decided to change the procedure for deep draw forming of the 0.060-inch blank. A fourth blank was hot formed in four

progressive steps, with the drop hammer punch moving approximately 1/4 inch into the tungsten sheet during each of the forming steps. The fourth blank also had several splits, 90 degrees apart, in the cup area. This failure also occurred during the final forming stage. The blank had partially stuck to the punch, resulting in minor surface melting of the punch tip. Although the deep drawing of 0.060-inch blank resulted in four failures, the forming tests indicated that with adequate process and tooling development, it may be possible to deep draw 0.060-inch tungsten sheet using Kirksite tools. This is based on the condition that the forming process, with proper tooling, does not create forming stresses and strains which will exceed the total uniform elongation and strength capabilities of the material. It is believed that failure of these blanks at the cup wall resulted from the transfer of the punch force at the bottom of the hemisphere to the cup wall due to a decreasing ratio of the punch cross sectional area to the blank area. As the drawing operation is continued, such as in progressive drawing steps, thinning occurs circumferentially in the cup wall near the punch radius and will result in premature failure from overstretching the material beyond its elongation limits. Therefore, if deep drawing of a comparatively small recess from a large blank is attempted, the punch force will develop radial tensile stresses which will approach the materials ultimate tensile strength. The metal will either tear or crack at a location where the tensile stresses are maximum. The failed deep drawn 0.060-inch tungsten sheet hemispheres after forming with a Kirksite punch and die are shown in Figure 27. The four failed deep drawn blanks were dimensionally checked to determine the mean diameter, cup depth, radius of formed hemisphere, percent stretch, strain distribution, and thickness variations. The results of this analysis are shown in Figures 28 through 30.

Based on the results obtained from this analysis, it was determined that this approach to deep drawing would be eliminated in favor of using conventional metal punch and die sets for evaluating the formability of deep drawn tungsten sheet.

A second set of deep drawing tools, consisting of a 1-3/4-inch diameter hemispherical punch and matching die cavity with a generous 0.84-inch radius, was fabricated from carbon steel. The deep drawing tools were mounted on a 35-ton Dake hydraulic press with a 7 inch per minute stroke. The forming blanks consisted of hot sheared 4-1/2 inch square, 0.060-inch and 0.100-inch sheet stock. The punch and die cavity was lubricated with a thin coat of molybdenum disulfide prior to heating the
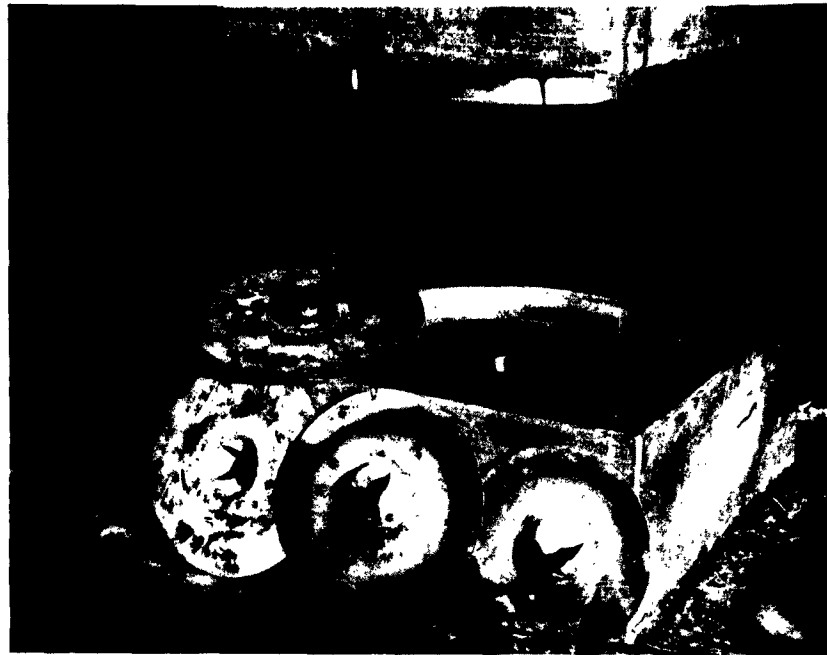
FIGURE 27. DROP HAMMER DEEP DRAWN TUNGSTEN SHEET; 0.060-inch

die. An oxyacetylene torch was used to preheat the steel die and punch to 600 F. The preheating prevented chilling of the tungsten sheet forming blanks. The 0.060-inch and 0.100-inch tungsten sheet blanks were heated on refractory furnace bricks with an oxyacetylene torch until a sheet temperature of 2100 F was reached. The temperature was monitored by Tempilstiks graduated in 100 degree F increments. This temperature was established for both sheet thicknesses due to the rapid loss of heat to the punch and die. When the appropriate forming temperature was reached, the heated blank was centrally located over the die cavity and the punch was pressed into the heated sheet to form the hemisphere. When the blank changed color from reduction in sheet temperature, the punch was retracted and the sheet was reheated to 2100 F. This procedure was repeated until the part cavity reached a depth of approximately 1/2 inch. The partially formed blank was abrasively trimmed to 2-1/2 inches in diameter, reheated to 2100 F, and replaced over the die cavity for the next stage of forming. The 2-1/2-inch diameter blank was die formed to approximately 80 percent of the total cavity depth at which time the punch was again retracted to reheat the partially formed part.
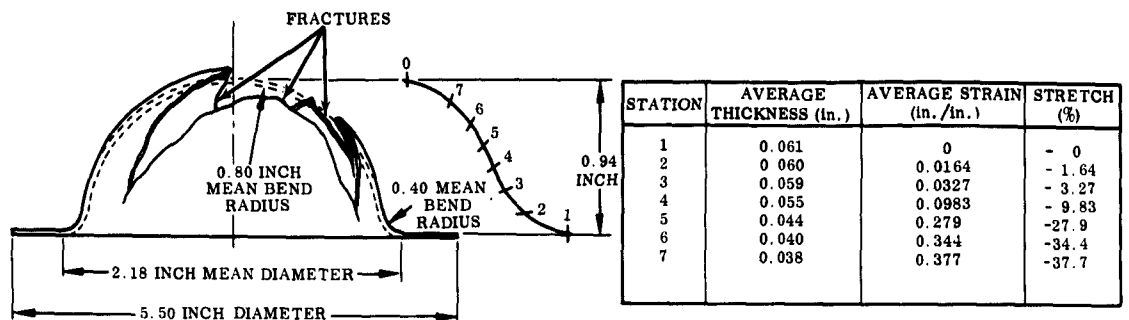
STATION	AVERAGE THICKNESS (in.)	AVERAGE STRAIN (in./in.)	STRETCH (%)
1	0.061	0	- 0
2	0 060	0.0164	- 1.64
3	0.059	0.0327	- 3.27
4	0.055	0.0983	- 9.83
5	0.044	0.279	-27.9
6	0.040	0.344	-34.4
7	0.038	0.377	-37.7

FIGURE 28.   ANALYSIS OF DROP HAMMER FORMED DEEP DRAWN TUNGSTEN;
Specimen No. 1

STATION	AVERAGE THICKNESS (in.)	AVERAGE STRAIN (in./in.)	STRETCH (%)
1	0.058	0.0491	- 4.91
2	0.060	0.0161	- 1.61
3	0.060	0.0161	- 1.61
4	0.058	0.0491	- 4.91
5	0.054	0.114	-11.4
6	0.046	0.213	-21.3
7	0.043	0.295	-29.5
8	0.037	0.393	-39.3
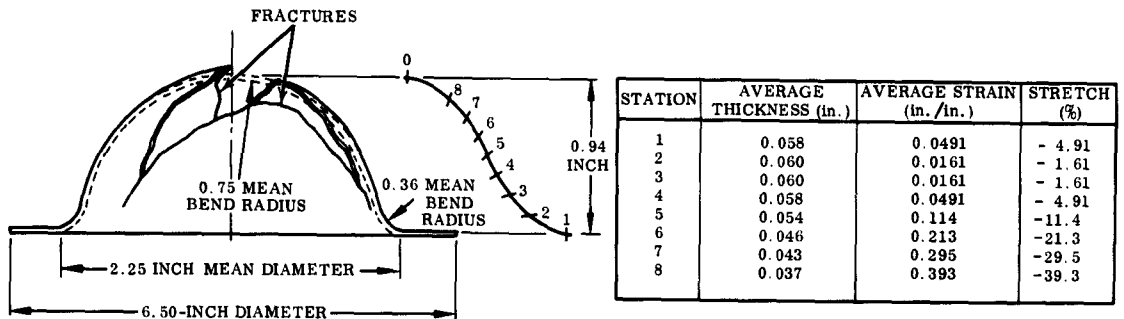
FIGURE 29.   ANALYSIS OF DROP HAMMER FORMED DEEP DRAWN TUNGSTEN;
Specimen No. 2

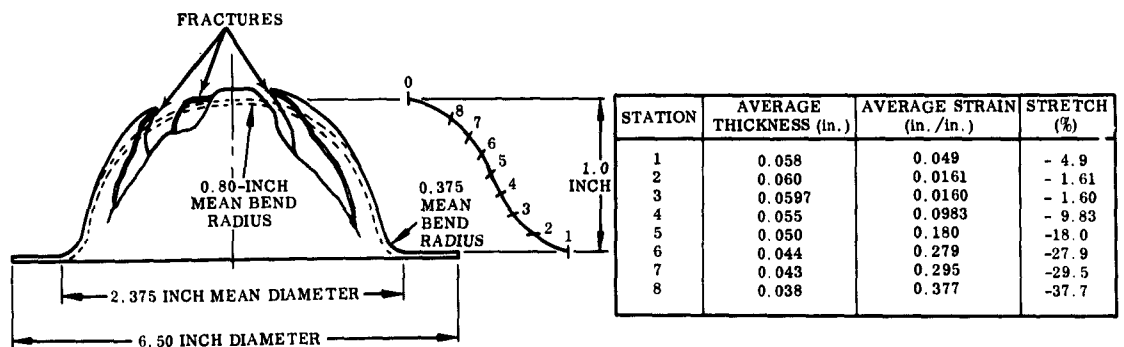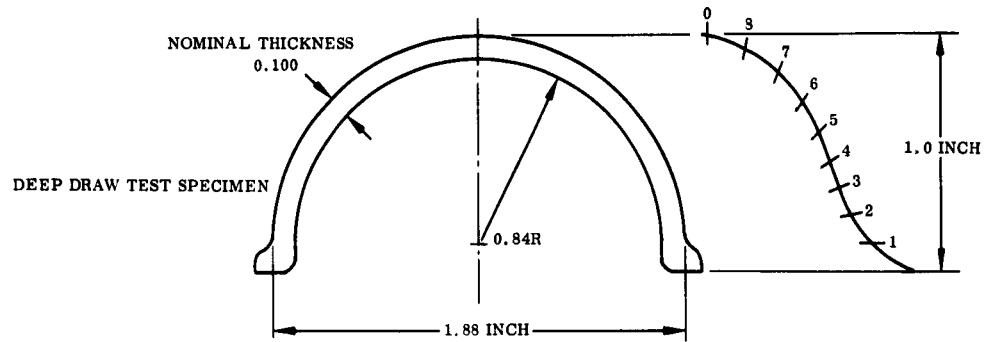| STATION	AVERAGE THICKNESS (in.)	AVERAGE STRAIN (in./in.)	STRETCH (%)
1	0.058	0.049	- 4.9
2	0.060	0.0161	- 1.61
3	0.0597	0.0160	- 1.60
4	0.055	0.0983	- 9.83
5	0.050	0.180	-18.0
6	0.044	0.279	-27.9
7	0.043	0.295	-29.5
8	0.038	0.377	-37.7

FIGURE 30.   ANALYSIS OF DROP HAMMER FORMED DEEP DRAWN TUNGSTEN;
Specimen No. 3

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The formed part was reheated and was subsequently bottomed in the die cavity under a pressure of 25 tons. This technique worked extremely well in producing satisfactory formed deep drawn hemispheres. The only failures from cracking occurred when blanks less than 4-1/2 inches square were used and wrinkles in the flange region developed before completion of the final forming operation. The various forming stages used to produce deep drawn 1-3/4-inch diameter hemispheres are shown in Figure 31. A number of deep drawn parts of 0.060- and 0.100-inch thick material were formed without any failures on this particular set of tools once the proper forming technique was established. The deep drawn hemispheres were checked dimensionally for mean diameter, cup depth, radius of formed hemisphere, thickness variations, strain distribution, and percent stretch. The results of an analysis on a typical deep drawn, 0.100-inch thick blank formed on a hydraulic press is shown in Figure 32. Contrary to the first set of deep drawn parts, in which failure occurred in all drop hammer formed parts regardless of the number of staging operations used, failure did not occur with a steel punch and die in a hydraulic press. The part was formed

FIGURE 31.   TEST SETUP FOR MULTISTAGE FORMING OF DEEP DRAWN
TUNGSTEN HEMISPHERES

STATION	AVERAGE THICKNESS (in.)	AVERAGE STRAIN (in./in.)	STRETCH (%)
1	0.103	0.030	+ 3.0
2	0.101	0.010	+ 1.0
3	0.100	0	0
4	0.092	0.080	- 8.0
5	0.079	0.21	-21.0
6	0.067	0.33	-33.0
7	0.076	0.24	-24.0
8	0.094	0.05	- 5.0

FIGURE 32. ANALYSIS OF HYDRAULIC PRESS FORMED DEEP DRAWN TUNGSTEN SPECIMENS

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from a rough blank in such a manner that the metal folded around the punch to form a recess and consequently is pulled away from the periphery towards the center. Although the total amount of stretch or strain was approximately the same as the Kirksite die formed parts, in this case there was more metal available from the upper blank region to satisfactorily deep draw without developing buckling or splitting in the cup wall due to high radial tensile stresses. The wrinkles which occurred in the upper flange region of the hemisphere were due to circumferential compression stresses. If the pressure during deep drawing is increased to stop wrinkling, premature splitting or cracking may result from the excessive force if attempts are made to iron out the wrinkles between the gap and punch.

It is planned to evaluate the deep drawing characteristics of the 0.010- and 0.020-inch thick sheet material utilizing the same type of forming tools used in the evaluation of the 0.060- and 0.100-inch tungsten sheet. After ascertaining the basic formability parameters required for the deep drawing of the various tungsten sheet gages, the investigation will be extended to cover the fabrication of deep drawn cups.

IV. FUTURE WORK

The following tasks are scheduled for the next reporting period:

1. Continue with radiant-heated, elevated-temperature, tensile tests of the four gages of tungsten sheet.

2. Establish the formability limits on the remaining forming studies for each gage of material considered.

3. Continue with developing and establishing joining parameters for tungsten sheet. It is planned to conduct elevated-temperature joint evaluation tests to select a joining technique(s) which provides the best overall joint properties for tungsten sheet material.

4. Conduct mechanical property determinations on each of the remaining forming studies after forming parameters are defined. Tests will be conducted where possible under similar conditions used in forming.

5. Conduct preliminary design studies for the fabrication of simple elements from tungsten sheet.

6. Conduct chemical analysis tests for carbon, oxygen, and nitrogen on several previously tested resistance heated tensile specimens to ascertain whether the low ductility at elevated temperatures may be due to surface contamination.

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REFERENCES

1. St. Germain, F. and Licciardello, M.R., Evaluation of RMSP Tungsten Sheet. Second Quarterly Progress Report, ER 1399-2, Solar, San Diego, California (January 1964).

2. Materials Advisory Board Report on Fansteel Tungsten Sheet Rolling Program, DMIC Report, Battelle Memorial Institute (March 1964).

3. Bodine, G.C., Jr., Tungsten Sheet Rolling Program, Final Report, Fansteel Metallurgical Corporation, North Chicago, Illinois (March 1963).

4. Sach's, G., Principles and Methods of Sheet-Metal Fabricating, Reinhold Publishing Company (1951).